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THE RIGIDITY OF THE EARTH

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In 1914, in the March number of the *Astrophysical Journal* (**39**, 105, 1914), an account was published of a preliminary experiment to determine the rigidity of the earth. At that time it was announced that the experiment would be repeated, using an interference method. The new arrangements were completed and a new series of observations begun on November 20, 1916, and continued until November 20, 1917. The reduction of the observations was interrupted by the war in the summer of 1917 and could not be resumed until April 1919.

The same pits and pipes on the grounds of the Yerkes Observatory at Williams Bay, Wisconsin, were used as in the preliminary experiment. In that experiment pipes 502 feet long and 6 inches in diameter were placed 6 feet underground. One pipe was laid accurately N–S and the other E–W. The pipes ended in pits 10 feet deep and 8 feet square, walled with concrete. The pipes were carefully leveled, and half filled with water, so that an air space extended from end to end of each pipe, above the water. The pipes ended in air-tight gauges provided with windows through which the changes in water-level could be determined by measuring with microscopes the distance between pointers just below the surface of the water and their totally reflected images.

In the present experiment interferometers replaced the microscopes and pointers. The arrangement of the interferometers, one at each end of each pipe, is shown in Figure 1. The compensating glass serves to seal the pipe. The lower mirror is movable vertically and has also the usual adjustments for regulating the width and orientation of the fringes. The film of water over this mirror is kept thin, usually about 0.5 mm, as the viscosity of the water

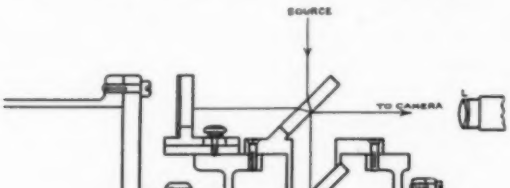


FIG. 1

helps to dampen ripples and minor disturbances. The changing thickness of the water film, due to the tides, caused the shift of fringes. The arrangement for recording the fringes was as follows: Horizontal fringes were projected by the lens *L* on a narrow vertical slit about 0.2 mm in width. Clockwork drew a moving-picture film behind this slit at the rate of about 2 cm per hour. In order to prevent the condensation of moisture on the optical parts the end of the pipe, interferometer, and camera were all inclosed in a galvanized iron box, in which large trays of calcium chloride were kept. An incandescent light was continually burning near the interferometer to keep the temperature slightly raised.

Other interference arrangements are obvious which would give a displacement of a greater number of fringes, or permit the use of a shorter pipe; e.g., the fringes formed between the water surface and the lower mirror might be used, or the lower mirror might be dispensed with and use made of the fringes formed by the light reflected from the water surface and the vertical mirror. But the arrangement actually used was the most satisfactory, since the long pipes, 502 feet, were already installed.

The sources of light were commercial alternating-current Cooper-Hewitt mercury lamps. They proved very reliable and satisfactory. By using as filters thin films of a saturated solution of esculin in water, all wave-lengths from the arc shorter than λ 4358 were absorbed, and the positive film used was not sensitive to the longer wave-lengths. The exposed portions of the films were removed and developed each week. The light was abundantly strong for satisfactory negatives, and it was possible to use 1.5 mm diaphragms on the projecting lenses. This gave sufficient sharpness to the fringes, even when there was a considerable change in their focus. It was necessary to readjust and refocus the fringes in only one pit during the entire year, although the width of the fringes was altered once or twice in two other pits. One of the mirrors required resilvering. One of the pits ran throughout the year without readjustment of the fringes or camera. The pits and cameras were in charge of Mr. George Monk and Mr. Frank Sullivan, of the Yerkes Observatory staff.

A relay which moved a shutter in front of the projecting lens was placed in each pit. The four relays were connected in series with a clock in the observatory, so that the time could be conveniently and accurately controlled. Once an hour the clock made contact, and a storage-battery circuit was closed through the relays and the light was cut off by the shutters for about 20 seconds. Very accurate time-marks were secured in this way. The control clock was kept six minutes faster than Central Standard Time in order to simplify the computations and bring the observations into agreement with them. (The longitude of Yerkes Observatory from Greenwich is $5^h\ 54^m\ 13^s$.)

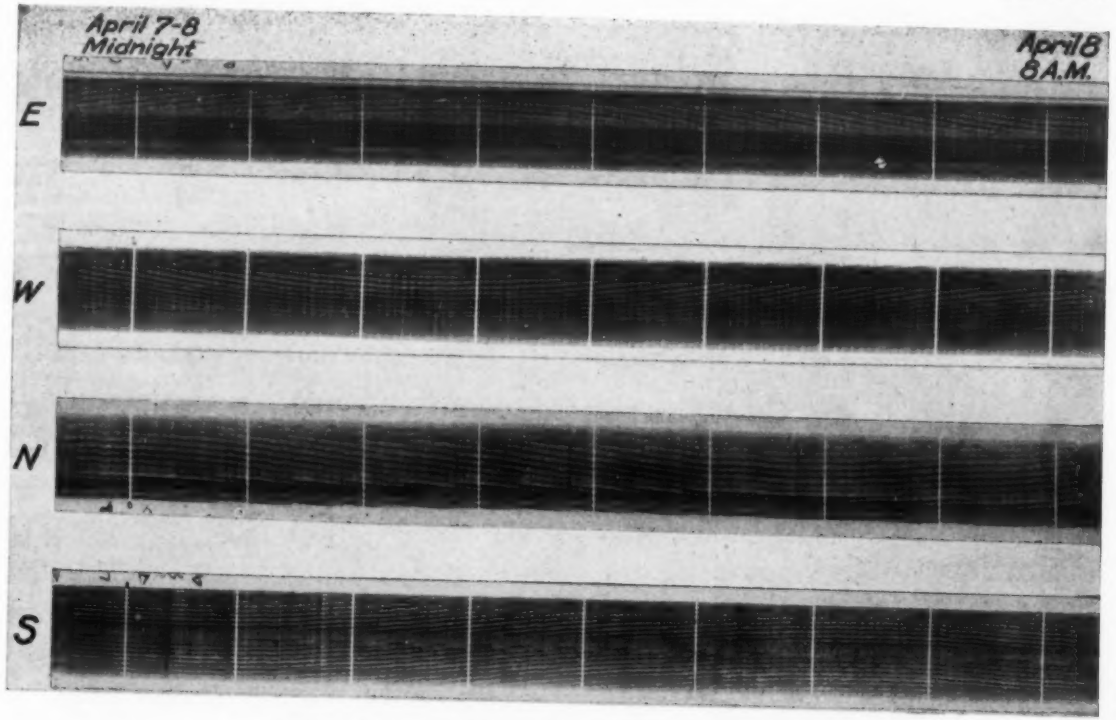
The films were measured by sliding them on a lathe-bed beneath a low-powered microscope. The fringes, estimated to tenths, were counted as they moved up and down, and the numbers recorded for each hour. The difference in the motion at the two ends of each pipe gave the numbers for plotting the observed tides.

The calculated tides were drawn from the computed shift in fringes, the calculations being made for two-hour intervals. The calculations were made under the direction of Professor F. R. Moulton by Mr. Albert Barnett and Mr. Horace Olsen. The formulae are given in the accompanying article by Professor Moulton, "Theory of Tides in Pipes on a Rigid Earth." The value of μ for the water used was found to be 1.3408 for λ 4358, and this is probably correct to within considerably less than 0.1 per cent for the range of temperatures used.

Calculated and observed curves for the period from March 24 to April 21, 1917, are reproduced in Figures 2 and 3. The dotted curve represents the observed and the full curve (displaced vertically to avoid overlapping) 0.7 of the calculated values of the tides. The ordinates are numbers of fringes, $N = \frac{2(\mu-1)d}{\lambda}$, and one fringe corresponds to 1/1564 mm.

The observed and calculated curves were plotted on long rolls of co-ordinate paper to the following scale: abscissae, 1 cm = 1 hour; ordinates, 1 cm = 2 fringes. In order to have the amplitudes approximately equal, 0.7 of the calculated values were plotted instead of the full amplitudes. Beginning with 10:00 A.M. November 20, 1916, the curves, both observed and calculated, were divided into periods of $12^h.42$ for the semi-diurnal and $25^h.82$ for the diurnal lunar tides. The principal solar tide, period twelve hours, was started at noon of the same day. In order to avoid a cumulative error in the case of the semi-diurnal lunar tide the period $12^h.4206013$ was put on a computing machine and added repeatedly to the initial time to get the exact beginning of each new period throughout the year. This process was repeated, using the period $25^h.8193409$ for the diurnal lunar tide.

The observations were reduced in groups of about a lunar month each, by dividing each period into ten equal parts (twelve



PHOTOGRAPHIC RECORDS TAKEN SIMULTANEOUSLY

in the case of the solar tide), and taking the mean of the first, second, third, etc., ordinates. The resulting values were plotted and any error in computation was usually indicated by the failure of a point to fall on a smooth curve. It is important to treat the observed and calculated tides both in the same way, as any distortion in the resulting sine curves due to lack of complete elimination of other periods affects the two alike. This is, of course, most noticeable in the case of the diurnal tide on account of its smaller amplitude and the smaller number of periods. Mr. Fred Pearson gave valuable assistance in measuring the films, in plotting the curves, and in deducing the various tides from the curves.

Very little trouble was caused by sudden erratic changes in the fringes. Occasionally, however, earthquakes would cause the fringes to disappear for from ten minutes to half an hour. Once the effects of an earthquake were evident for about six hours. During three hours of this time the fringes were completely obliterated.

The most serious disturbance was a gradual change in the slope of the observed curves. This would often be fairly uniform and gradual for a month or two. At some times the curves would rise and at others fall. Sometimes the N–S and E–W slopes had the same sign, and sometimes opposite signs. We have been able to discover nothing systematic about this drifting. It may have been caused by unequal settling at the ends of the pipes, by temperature changes in the pits, or by tilting in the earth's strata. There were always large shifts of the fringes when the lights came on after having been interrupted by the power company for a half-hour or so. The change of slope was eliminated in reducing each monthly tide, as given in Tables I–VI, and the tide for the whole year, opposite *Y* in the tables, by distributing the change of level uniformly throughout the period. This change of slope is quite conspicuous in Figure 3, where the observed E–W tide showed a fairly uniform and distinct downward trend throughout nearly the whole month. The change in slope of the N–S curves for the same period is comparatively small, as shown in Figure 2.

Plate III is from four photographs taken simultaneously in the four pits. The reproductions are positives on the same scale

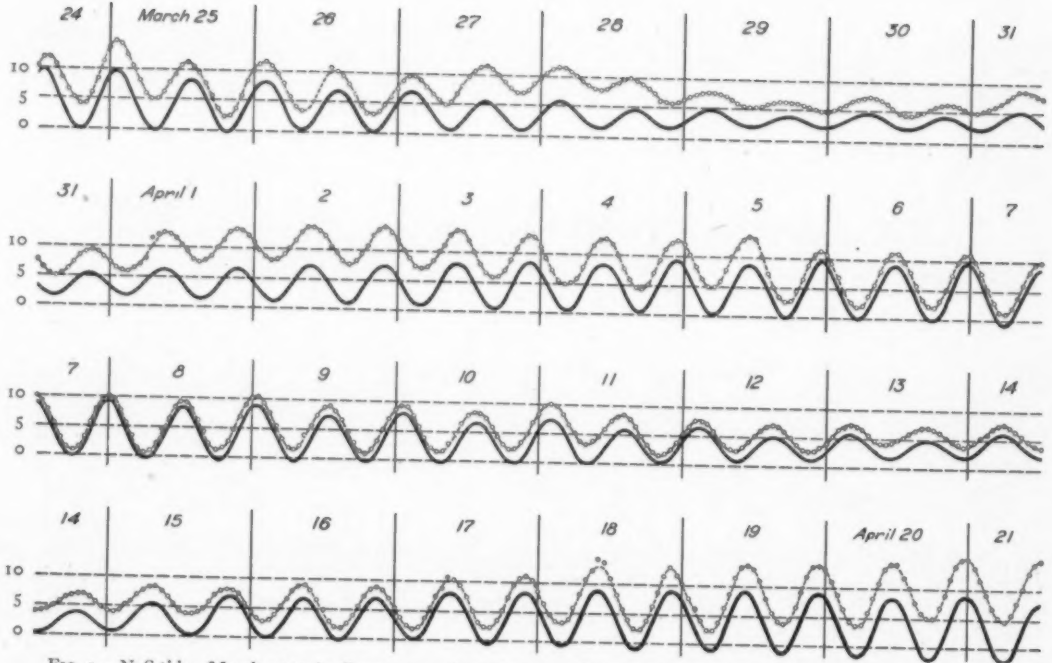


FIG. 2.—N–S tides, March 24 to April 21, 1917. Dotted curves, observed values. Full curves, 0.7 of calculated values

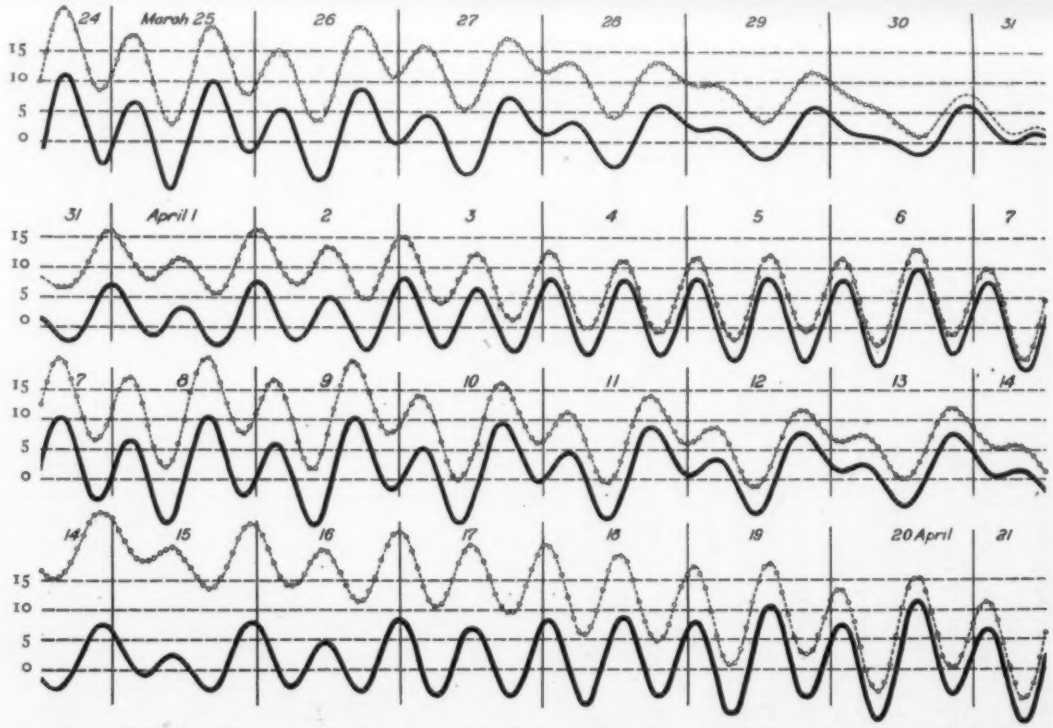


FIG. 3.—E–W tides, March 24 to April 21, 1917. Dotted curves, observed values. Full curves, 0.7 of calculated values

as the originals, and represent fairly well the average quality of the films.

A graphical solution is excellent for detecting erroneous points and serves well to give the ratio of the observed to the calculated amplitude, but for determining the phase-difference of the two curves it is not so satisfactory. A least-squares method was therefore used to secure the ratio of amplitudes, R, and the displacement in phase $\Delta\phi$ of the observed with respect to the calculated tide. The following example illustrates the method of reduction. It is for the semi-diurnal tide, first month, E–W. For convenience the solar periods were divided into twelve parts instead of ten, but in other respects the method of reduction is the same.

In Tables I–VI the numbers in the columns under M denote the different approximate lunar months; under N is given the number of periods used. For the solar tides missing portions of the observed curves were sketched in, following the computed tides, thus giving a total of 730 periods for the year, but for the semi-

FIRST MONTH, SEMI-DIURNAL, E–W OBSERVED

θ	y	Sin θ	y Sin θ	Cos θ	y Cos θ
0°	17.58	0.0000	0.0000	1.0000	17.5800
36	18.74	.5878	11.0153	0.8090	15.1606
72	15.73	.9511	14.9608	.3090	4.8605
108	10.46	.9511	9.9485	− .3090	−3.2321
144	4.83	.5878	2.8390	− .8090	−3.9074
180	0.60	.0000	0.0000	−1.0000	−0.6000
216	−0.20	− .5878	0.1234	−0.8090	0.1698
252	2.58	− .9511	−2.4538	− .3090	−0.7972
288	7.76	− .9511	−7.3805	.3090	2.3978
324	13.48	− .5878	−7.9235	.8090	10.9053
Total			+21.1292		+42.5373

$$\alpha=\frac{21.1292}{5}=+4.2258 \qquad \beta=\frac{42.5373}{5}=+8.5075$$

$$\tan\phi_c=\frac{\beta}{\alpha}=2.0132$$

$$\phi_c=63°35'$$

$$c=\sqrt{\alpha^2+\beta^2}$$

$$c=\sqrt{90.2350}$$

$$c=9.499$$

$$y=9.499\sin(\theta+63°35')$$

FIRST MONTH, SEMI-DIURNAL, E–W CALCULATED

θ	y	Sin θ	y Sin θ	Cos θ	y Cos θ
0°	17.38	0.0000	0.0000	1.0000	17.3800
36	18.89	.5878	11.1035	0.8090	15.2820
72	16.73	.9511	15.9119	.3090	5.1695
108	11.58	.9511	11.0137	− .3090	−3.5782
144	6.13	.5878	3.6032	− .8090	−4.9591
180	0.90	.0000	.0000	−1.0000	−0.9000
216	0.00	− .5878	.0000	−0.8090	.0000
252	2.23	− .9511	−2.1209	− .3090	− .6890
288	7.16	− .9511	−6.8098	.3090	2.2124
324	12.91	− .5878	−7.5885	.8090	10.4441
Total			+25.1131		+40.3617

$$\alpha=\frac{25.1131}{5}=+5.0226 \qquad \beta=\frac{40.3617}{5}=+8.0723$$

$$\tan \phi_d=\frac{\beta}{\alpha}=+1.6072$$

$$\phi_d=58°7'$$

$$d=\sqrt{\alpha^2+\beta^2}$$

$$d=\sqrt{90.3885}$$

$$d=9.507$$

$$y=9.507 \sin (\theta+58°7')$$

$$R=\frac{c}{d}\frac{0.7\times 9.499}{9.507}=0.699 \qquad \Delta\phi=\phi_c-\phi_d=+5°28'$$

diurnal and diurnal lunar tides only such portions of the observed curves were used as gave complete periods. Under a and c are given the amplitudes and under ϕ_a and ϕ_c the phase constants for the observed curves and under b and d and ϕ_b and ϕ_d the corresponding quantities for the calculated curves. In taking the means the value for each month is weighted in proportion to the number of periods in the month. Below the mean R and $\Delta\phi$ in each case is given the average difference from the mean. At the bottom of each table opposite Y are given the results obtained by computing the tides for the entire year as a single period instead of for a month at a time. The results agree closely with the means for the thirteen months, and are shown graphically in Figures 4 to 8.

Violent storms broke down the electric wires during February and March on several occasions, interrupting the electric current for a few hours. The pits cooled, and there were resulting large

shifts of the fringes after the current was re-established. It seems highly probable that the large difference of phase which is shown for the fourth month E–W diurnal tide is due to such disturbances.

TABLE I

N–S, SEMI-DIURNAL, LUNAR

M	N	a	b	ϕ_a	ϕ_b	R	$\Delta\phi$
1.....	60	6.217	6.373	149°14′	147°48′	0.683	1°26′
2.....	54	5.703	6.489	147 53	144 4	.615	3 49
3.....	48	7.261	6.780	146 15	145 56	.750	0 19
4.....	45	6.750	6.739	148 44	146 23	.701	2 7
5.....	55	6.041	6.269	148 37	148 54	.675	−0 17
6.....	54	6.426	6.551	148 35	147 57	.687	0 38
7.....	54	6.332	6.344	148 40	145 56	.699	2 44
8.....	51	6.052	6.344	147 47	146 58	.668	0 49
9.....	55	6.036	6.319	146 36	147 16	.669	−0 40
10.....	54	5.821	6.210	149 27	147 32	.656	1 55
11.....	54	5.875	6.140	148 14	148 16	.670	−0 2
12.....	55	6.027	6.284	149 18	147 46	.671	1 32
13.....	45	6.330	6.515	152 39	150 36	0.680	2 3
Av....	.....	6.203	.....	.....	.....	0.678 ± .019	1°15′ ±1 2
Y	684	6.173	6.401	148°24′	147°32′	0.675	0 52

TABLE II

E–W, SEMI-DIURNAL, LUNAR

M	N	c	d	ϕ_c	ϕ_d	R	$\Delta\phi$
1.....	60	9.499	9.507	63°35′	58° 7′	0.699	5°28′
2.....	54	8.908	9.096	64 40	58 5	.686	6 35
3.....	48	9.899	10.075	61 28	55 47	.688	5 41
4.....	43	10.220	10.369	69 46	65 2	.690	4 44
5.....	56	9.131	9.380	63 43	57 0	.681	6 43
6.....	53	9.660	9.667	65 4	57 54	.700	7 10
7.....	54	9.496	9.632	64 26	57 6	.690	7 20
8.....	51	9.445	9.331	60 48	55 4	.709	5 44
9.....	55	9.206	9.316	63 24	57 30	.692	5 54
10.....	54	8.773	9.095	64 52	56 32	.675	8 20
11.....	54	8.982	9.108	61 31	57 18	.690	4 13
12.....	55	9.138	9.337	63 12	58 12	.685	5 0
13.....	45	9.809	9.747	67 20	61 44	0.704	5 36
Av....	.....	9.373	.....	.....	.....	0.691 ± .007	6° 4′ ± 55
Y	682	9.380	9.485	63°56′	58°10′	0.692	5 46

Moreover, this month, on account of the interruptions, contained but 20 periods instead of the usual 26. The mean is therefore given for twelve lunar months, omitting the fourth, on the line Av_{12} as

TABLE III

N–S Solar

M	*N*	*a*	*b*	ϕ_a	ϕb	*R*	$\Delta\phi$
1.....	56	2.554	2.628	104° 8′	99°39′	0.680	4°29′
2.....	62	2.392	2.294	100 13	85 45	.730	14 28
3.....	48	4.883	4.272	93 34	82 59	.800	10 35
4.....	70	2.778	3.132	88 41	80 35	.621	8 6
5.....	58	3.840	3.744	100 26	97 14	.718	3 12
6.....	54	3.595	3.485	102 43	99 59	.722	2 43
7.....	56	2.818	2.570	109 29	103 27	.768	6 2
8.....	54	2.513	2.312	109 1	99 49	.761	9 12
9.....	56	2.771	2.506	87 23	84 18	.774	3 5
10.....	56	2.944	3.108	89 35	86 54	.663	2 41
11.....	56	3.562	3.456	99 10	95 51	.721	3 19
12.....	56	3.154	3.291	108 6	103 40	.671	4 26
13.....	48	3.775	3.889	98 55	99 38	0.679	−0 43
Av....	.....	3.161	.....	.....	.....	0.714 ±.041	5°38′ ±3 16
Y	730	3.140	3.063	99°25′	93°20′	0.718	6 5

TABLE IV

E–W Solar

M	*N*	*c*	*d*	ϕ_c	ϕ_d	*R*	$\Delta\phi$
1.....	56	3.641	3.838	13°54′	9°40′	0.664	4°14′
2.....	62	3.218	3.400	3 31	355 40	.663	7 51
3.....	48	6.172	6.488	358 28	352 59	.666	5 29
4.....	70	4.444	4.665	354 5	350 14	.667	3 51
5.....	58	5.534	5.480	11 19	6 33	.707	4 46
6.....	54	5.104	5.173	16 52	10 59	.691	5 53
7.....	56	3.687	3.731	21 32	13 53	.692	7 39
8.....	54	3.487	3.407	15 3	8 22	.716	6 41
9.....	56	3.450	3.689	359 50	353 28	.655	6 22
10.....	56	4.371	4.595	3 14	356 36	.666	6 38
11.....	56	5.045	4.993	7 57	4 32	.707	3 25
12.....	56	4.689	4.858	16 28	14 16	.676	2 12
13.....	48	5.621	5.626	10 0	6 11	0.699	3 49
Av....	.....	4.459	.....	.....	.....	0.681 ±.018	5°19′ ±1 28
Y	730	4.399	4.522	8° 6′	2°23′	0.681	5 43

TABLE V

N–S, Diurnal, Lunar

M	N	a	b	ϕ_a	ϕ_b	R	$\Delta\phi$
1.....	26	0.962	0.551	185°35′	193°24′	1.222	− 7°29′
2.....	28	0.653	.470	189 59	188 19	0.973	1 40
3.....	24	1.306	.550	319 49	201 31	1.662	118 18
4.....	20	2.042	.701	305 43	218 48	2.039	86 55
5.....	25	0.117	.509	189 00	203 36	0.336	−14 36
6.....	26	.347	.465	218 59	197 7	.522	21 52
7.....	26	.335	.499	190 27	194 25	.475	− 3 58
8.....	25	.279	.484	193 22	193 25	.404	− 0 3
9.....	26	.297	.463	213 32	195 58	.451	17 34
10.....	26	.538	.473	154 44	193 31	.796	−38 37
11.....	26	.277	.455	164 41	194 4	.426	−29 23
12.....	26	.282	.365	214 36	188 58	.541	+25 38
13.....	22	0.359	0.480	181 1	191 58	0.523	−10 57
Av_{13}...	.....	0.574	.....	.....	.....	0.777 ±0.411	11°57′ ±30 49
Av_{12}...	.....	0.478	.....	.....	.....	0.694 ±0.313	7 3 ±26 6
Av_{11} ..	.....	0.408	.....	.....	.....	.612 ±0.216	− 2 25 ±16 12
Y_{13} ...	326	0.281	0.503	229°23′	197°57′	0.411	31 26
Y_{12} ...	306	0.298	0.492	203 24	196 07	.424	7 17
Y_{11} ...	282	0.411	0.489	188 14	196 56	0.588	− 8 42

TABLE VI

E–W, Diurnal, Lunar

M	N	c	d	ϕ_c	ϕ_d	R	$\Delta\phi$
1.....	26	4.107	3.819	282° 9′	284°56′	0.753	−2°47′
2.....	28	3.845	3.725	275 48	278 19	.723	−2 31
3.....	24	4.164	4.193	288 57	288 58	.695	−0 1
4.....	20	3.525	3.603	317 6	293 57	.685	23 9
5.....	25	3.925	4.134	287 31	285 43	.665	1 48
6.....	26	3.517	3.850	291 19	288 14	.639	3 5
7.....	26	3.925	3.900	281 44	285 13	.704	−3 29
8.....	25	4.032	3.968	281 54	281 24	.711	0 30
9.....	26	3.710	3.518	286 41	283 20	.738	3 21
10.....	26	3.480	3.595	282 29	284 21	.678	−1 53
11.....	26	3.383	3.442	281 40	283 59	.688	−2 19
12.....	26	3.439	3.470	278 57	281 36	.694	−2 39
13.....	22	4.526	4.485	275 17	280 35	0.706	−5 18
Av_{13}...	326	3.807	.....	.....	.....	0.699 ±0.022	0°29′ ±4 11
Av_{12} ..	306	3.825	.....	.....	.....	0.700 ±0.024	−1 0 ±2 8
Y_{13} ...	326	3.759	3.799	284°55′	283°22′	0.693	1 33
Y_{12} ...	306	3.807	3.815	283 52	282 43	0.699	1 9

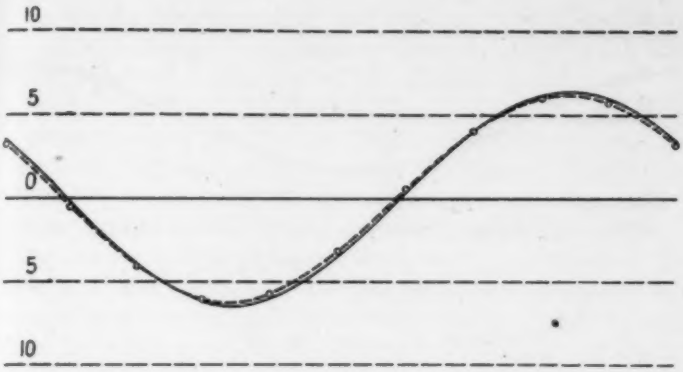


FIG. 4.—N–S semi-diurnal lunar tide for entire year. Dotted curve from observed values

$$y=6.173 \sin (\theta+148^\circ 24')$$

Full curve from 0.7 calculated values

$$y=6.401 \sin (\theta+147^\circ 32')$$
$$R=0.7\ a/b=0.675.\quad \Delta\phi=52'$$

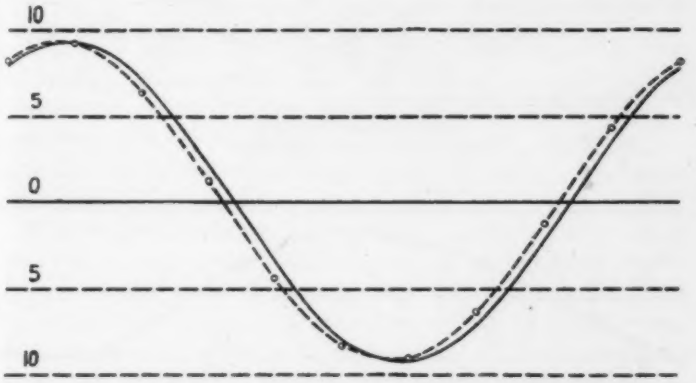


FIG. 5.—E–W semi-diurnal lunar tide for entire year. Dotted curve from observed values

$$y=9.380 \sin (\phi+63^\circ 56')$$

Full curve from 0.7 of calculated values

$$y=9.485 \sin (\theta+58^\circ 10')$$
$$R=0.7\ c/d=0.692.\quad \Delta\phi=5^\circ 46'$$

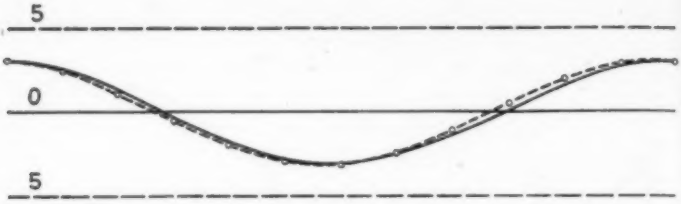


FIG. 6.—N–S solar tide for entire year. Dotted curve from observed values

$$y = 3.140 \sin (\theta + 99°25')$$

Full curve from 0.7 of calculated value

$$y = 3.063 \sin (\theta + 93°20')$$
$$R = 0.7\ a/b = 0.718. \quad \Delta\phi = 6°5'$$

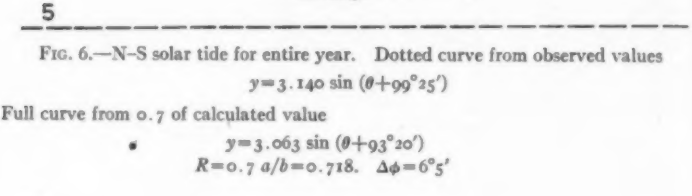


FIG. 7.—E–W solar tide for entire year. Dotted curve from observed values

$$y = 4.399 \sin (\theta + 8°6')$$

Full curve from 0.7 of calculated value

$$y = 4.522 \sin (\theta + 2°23')$$
$$R = 0.7\ c/d = 0.681. \quad \Delta\phi = 5°43'$$

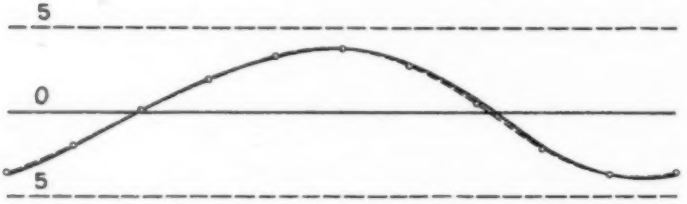


FIG. 8.—E–W diurnal lunar tide for entire year. Dotted curve from observed values

$$y = 3.759 \sin (\theta + 284°55')$$

Full curve from 0.7 of calculated values

$$y = 3.799 \sin (\theta + 282°53')$$
$$R = 0.7\ c/d = 0.693. \quad \Delta\phi = 1°33'$$

well as for the thirteen months. A calculation for 306 periods was also made, omitting this month from both the observed and calculated data. This value is given opposite Y_{12}.

In the case of the N–S diurnal tide it will be noted that the amplitude is very small, about 0.5 fringe, as it should be since this tide has the coefficient cos $2l$, where l is the latitude. For Yerkes Observatory cos $2l = 0.0848$. This tide is too small to admit of much accuracy in the determination, but the results are included, as they are not without interest. Mean values are added for the whole year, and the means omitting the fourth month, and also omitting both the third and the fourth. The calculations are also added for the year as a whole, 326 periods; omitting the fourth month, 306 periods; and omitting both the third and fourth months, 282 periods. The omission of these months is perhaps justified, since both R and $\Delta\phi$ are decidedly abnormal. The mean of the six values gives $R = 0.584$ and $\Delta\phi = 7°46'$. Probably the only conclusion which is justified for the N–S diurnal tide is that R is about $0.6 \pm .2$ and that the difference of phase is small.

An effort was made to deduce the fortnightly lunar tide of period 13.66 days. Here the E–W tide should be zero, and the residual sine curves were less than 0.05 fringe from both the calculated and observed curves. The N–S tide, however, had an amplitude of about 1.8 fringes and gave $R = 0.628$ and $\Delta\phi = -8°24'$, quantities which agree as well as could be expected with the shorter periods. The negative sign of $\Delta\phi$ merely indicates that the uncertainty is considerable.

The results are collected in Table VII. The value given in each case is the average of the mean value for the thirteen lunar months and the value deduced by treating all the observations in a single set, except in the case of the N–S diurnal tide, where the values given are the mean of the six determinations mentioned above, and in the case of the E–W diurnal tide, which is the mean of four similar determinations.

The amplitudes are those for the observed curves averaged as indicated above. The errors indicated for the different tides are the average differences from the means of the thirteen months, except in the case of the N–S diurnal tide, where it is simply an

estimate. In combining the different tides to get a mean in each direction, the ratios and phase differences were weighted in proportion to the amplitudes of the tides except that the N–S diurnal tide was omitted. The final means of R and $\Delta\phi$ are the mean values obtained by weighting the five determinations in this way.

TABLE VII

	N–S			E–W		
	Amp.	R	$\Delta\phi$	Amp.	R	$\Delta\phi$
Lunar semi-diurnal...	6.188	0.6765 ± .019	1°15′ ± 1°2′	9.376	0.6915 ± .007	5°54′ ± 56′
Solar.....	3.150	0.716 ± .041	5°53′ ± 3°12′	4.429	.681 ± .018	5°30′ ± 1°28′
Lunar diurnal.....	.408	0.584 ± .200	(7°46′ ± 15°)	3.799	.698 ± .023	38′ ± 3°28′
Weighted means...	.....	0.6895	2°41′	.....	0.6903	4°34′
Final values		$R = 0.690 \pm .004$			$\Delta\phi = 4°$	

This seems to be the most logical procedure and is perhaps justified by the fact that the average difference from the mean for the different tides in each direction is roughly inversely proportional to the amplitude. The probable error, computed in the usual way, is given with the final value of R.

The final result indicates that the rigidity of the earth in the N–S and E–W directions is the same[1] and the ratio R is 0.690 with a probable error of ±0.004. That the viscous yielding of the earth is small is indicated by the small difference in phase between the observed and computed tides. It will be noted that the two solar tides appear to agree excellently in phase displacement with the E–W semi-diurnal tide and that for the N–S semi-diurnal, and probably also the E–W diurnal lunar tides the phase displacement is definitely smaller.

However, for lack of a better method of finding the means of the N–S and E–W phase displacement, each was averaged as the ratios were, that is, simply by weighting them in proportion to the amplitudes of the tides. This gives a displacement in phase of

[1] The preliminary experiment, through an error in computation, indicated a difference in the rigidities in the two directions. The ratio should have been 0.710 for both the N–S and E–W. See *Science*, October 3, 1919, p. 327.

the water tides in the N–S direction of $+2°41'$ and in the E–W direction $+4°34'$. Although it seems certain that the difference in phase is slightly larger in the E–W than in the N–S direction, a mean displacement of $+4°.0$ is probably correct to within $1°$. If we take $R=0.690$, the tides in the actual earth are 0.310 of what they would be if the earth were fluid, and the value of $\Delta\phi$ equal to $4°.0$, for the displacement of the water tides means that the earth tides lag behind the impressed forces by this same amount.

It is desired to express appreciation of the interest taken in this work by Professor T. C. Chamberlin, Professor E. B. Frost, and Professor F. R. Moulton.

RYERSON LABORATORY
November 1919

A PECULIAR BELT OF OBLIQUE FAULTING

ROLLIN T. CHAMBERLIN
University of Chicago

The Rocky Mountain system is a belt of varying structure. Northward from northern Montana it is a sharply delineated chain bordered on its eastern margin throughout many degrees of latitude by great overthrust faults. But in central Montana the regular, linear, faulted chain loses much of its distinctiveness and gives way to an irregular group of scattered mountain clusters.[1] Farther south in Wyoming and Colorado the Rockies reassemble in a more definite continuous chain, but in these latitudes folding has replaced faulting as the dominant structure.

For the present paper it is important to note that in central and southern Montana the Rocky Mountain chain, which elsewhere constitutes the definite backbone of the continent, spreads out into a plexus of short minor ranges and isolated mountain groups. These reach far out into the Great Plains province, where each of the individual groups becomes essentially a unit by itself. Some have resulted from igneous outbursts, and exhibit the results of vertically acting forces fully as much as horizontal thrusting; others have arisen largely from faulting or folding. In consequence of this diversity of origin of the major features, the general region has been subjected to stresses of quite variable sorts. It is to emphasize the peculiar manifestation of some of these that the present paper is ventured.

From the vicinity of Billings, in the midst of this region of scattered uplifts, E. T. Hancock has recently described a very remarkable belt of faulting, some 56 miles in length and comprising over 90 separate faults, relatively close together and more or less parallel one to another.[2] A striking feature of the belt is that

[1] Rollin T. Chamberlin, "The Building of the Colorado Rockies," *Jour. Geol.*, XXVII (1919), pp. 147–48.

[2] E. T. Hancock, "Geology and Oil and Gas Prospects of the Lake Basin Field, Montana," *U.S. Geol. Survey*, Bull. 691-D (1918), pp. 101–47.

the fault lines, practically without exception, are inclined in the neighborhood of 45° to the long dimension of the faulted strip (Fig. 1). Many of these faults are over 5 miles in length, while one slightly curving fault plane has been traced for fully 10 miles. A few of the shorter faults, however, are less than a mile in length. As mapped by Hancock, these faults cut through a region surfaced by the Colorado and Montana groups of the Cretaceous, and by the Lance formation of the early Tertiary.

Hancock has clearly brought out the fact that the belt of faulting is located on the flanks of two conspicuous domes, which are the two dominating folds of the Lake Basin field. These are the Big Coulee–Hailstone dome in the northwest portion of the area studied, and the end of the Big Horn Mountain anticline, which extends into the southeastern corner of the Lake Basin field.[1] Southeast of the Big Coulee–Hailstone dome, in the direction of its principal axis, is a minor circular uplift which the author has called the Broadview dome. Hancock has pointed out the fact that the most intense faulting occurred along the steeply dipping south flank of the Big Coulee–Hailstone dome and around the southeast side of the Broadview dome.[2] From the Broadview dome to the northwest end of the Big Horn Mountain anticline very few faults were observed, but on the northwest slopes of the latter uplift they again become numerous. In short, the faulted strip follows the southern flank of the Big Coulee–Hailstone dome (including its satellite, the Broadview dome) and, after crossing an intermediate area where there are fewer faults, continues in nearly a straight line along the northern flank of the Big Horn uplift.

Both the doming and the faulting, which may perhaps be termed the local structural features of the Lake Basin field, are regarded by the author as in all probability related in origin to the major structures of the general region, and to have been determined more or less by the complex forces involved in the development of these major structures. "The mountain masses whose development has probably been the most active in determining the nature of the minor structural features in the vicinity of the Lake Basin field

[1] *Ibid.*, pp. 133–34.

[2] *Ibid.*, p. 136.

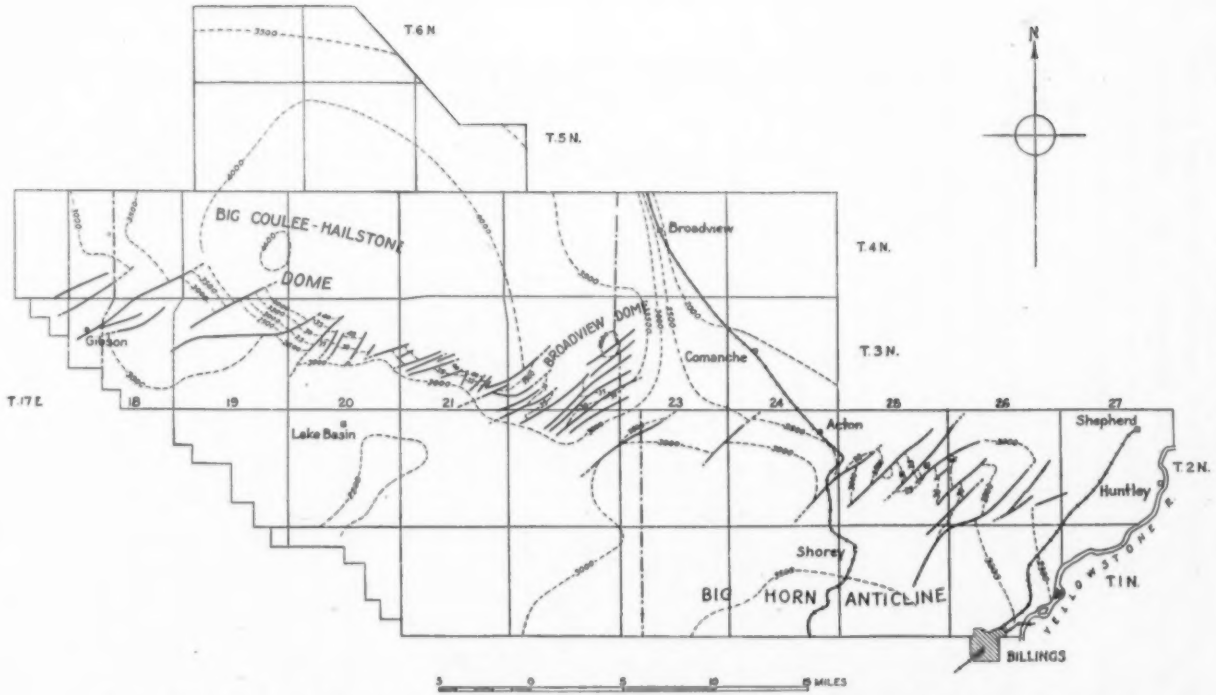


FIG. 1.—Map of the belt of faults in the Lake Basin field, Montana. The individual faults are inclined in the neighborhood of 45° to the long dimension of the belt. The dotted lines represent the structure contours on the base of the Eagle sandstone. Contour interval 500 feet. These contours depict the Big Coulee–Hailstone dome in the northwest portion of the area and the end of the Big Horn uplift in the southeast portion. (Redrawn from E. T. Hancock.)

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are the Big Snowy Mountains on the north, the Little Belt Mountains on the northwest, the Snowy Range on the southwest, and the Big Horn Mountains on the southeast."[1] In three of these ranges the uplift has been so great that the pre-Cambrian complex is now exposed in the central core. Igneous outbursts have occurred in the general region, though not recognized within the Lake Basin field itself. The general setting of this remarkable faulting is admirably portrayed in this *Bulletin*, and many suggestive details are brought to the front, but as no definite explanation of the faulting is offered, I herewith venture to suggest some of the possible factors which may have given rise to the phenomenon.

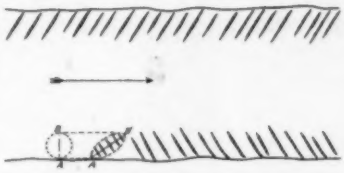

FIG. 2.—Diagram to illustrate the formation of oblique crevasses along the margins of a glacier moving in the direction indicated by the arrow. The crevasses point upstream as they extend toward the middle of the glacier where the motion is more rapid.

POSSIBLE EXPLANATIONS

There are two familiar processes which are known to produce parallel fracturing in a zone such as described. The first is illustrated by the development of oblique crevasses along the margins of valley glaciers. As the middle portion of a glacier moves more rapidly than the ice near the sides, a line on the glacier connecting points A and B (Fig. 2) will, after a time, become A′B′.[2] Since A′B′ is longer than AB, there has been stretching along that line. In fact, it can readily be shown that A′B′ represents the direction of elongation, or major axis of the strain ellipsoid, as developed by Leith.[3] Tension therefore develops along this line, and is relieved by fractures at right angles to it. Hence it is that the lateral margins of valley glaciers are commonly riven by a great

[1] E. T. Hancock, *op. cit.*, p. 132.

[2] John Tyndall, *Glaciers of the Alps* (1860), pp. 318–19.

[3] C. K. Leith, *Structural Geology* (1913), pp. 16–21.

It is of course to be recognized that, since the rate of motion changes more rapidly near the margin of the glacier than toward the middle, the line A′B′ will be curved instead of straight, and ideally the relation should be represented by many small strain ellipsoids instead of one large one.

...feet. These contours depict the Big Coulee–Hailstone dome in the northwest portion of the area and the end of the Big Horn uplift in the southeast portion. (Redrawn from E. T. Hancock.)

succession of parallel crevasses which point obliquely upstream as they extend in toward the middle of the glacier. Such a belt of crevasses bears some resemblance to the belt of faults in the Lake Basin field.

The other process which is known to produce results of this kind is torsion. Its behavior has been strikingly illustrated by the familiar experiment of Daubrée, who subjected a long plate of glass to torsional stress.[1] The result was to produce numerous fractures in two distinct sets which crossed each other approximately at right angles (Fig. 3). The fractures of each set were nearly parallel to one another, and were inclined approximately at 45° to the axis of torsion. Either set of parallel fractures would look much like the strip of faults in the Lake Basin field, provided the other intersecting set did not form.

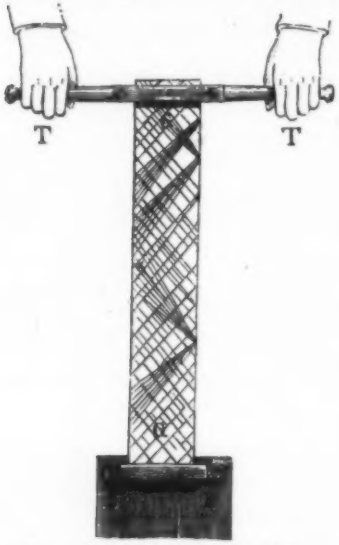

FIG. 3.—Fractures developed in a glass plate by torsion. The two sets of fractures are nearly at right angles to each other and inclined 45° to the axis of torsion. (From Daubrée.)

APPLICATION TO THE LAKE BASIN FAULTING

The most striking characteristic of this belt of faulting in Montana is the grouping of the faults in a long, narrow strip trending W.N.W. and E.S.E. Scarcely less conspicuous is the fact that, almost without exception, the individual fault traces are inclined to the axis of the belt at angles in the general vicinity of 45°. The third fact of prime significance appears to be that toward the west end of the belt the fracturing took place on the south flank of an uplifted tract, while toward the east end of

[1] G. A. Daubrée, *Études synthétiques de géologie expérimentale* (1879), Tome 1, pp. 307–15.

the belt the fracturing has occurred on the north flank of another distinct uplift. In the area between the two uplifts there has been some but noticeably very much less faulting than on the immediate flanks of the two uplifts. In the process of doming, the strata near the west end of the faulted strip were uplifted on the north and given a southerly tilt, while near the east end of the zone of faulting the strata were uplifted on the south and thus given a northerly tilt. Thus the two ends of the faulted area were tilted in opposite directions. Such an opposite movement involves a certain amount of twisting, or torsion. The axis of the twist would coincide with the long axis of the present fault belt. If the strains developed in this adjustment between the oppositely tilted areas were sufficiently great, they would produce fracturing along planes inclined approximately 45° to the axis of torsion, or long dimension of the present faulted belt. Daubrée's experiment would suggest that these fractures should occur in two sets crossing each other at right angles. One such set, to the number of more than 90 faults, is in just the position to meet the requirements, but the complementary set, with the exception of two very short faults northeast of the Broadview dome, is lacking.

The explanation of the failure of the cross-fractures to open is sought in the trend of the axis of torsion, whose general direction hovers around N.80°W. The fractures of the set which actually did form have a N.E.-S.W. trend. If the complementary set of fractures had developed, they also should have opened in planes inclined 45° to the axis of torsion and at right angles to the first set, which would place them in the neighborhood of N.35°W. It will be observed that this last figure is not far from the general trend of the adjacent portion of the Rocky Mountains. The Rocky Mountains owe their formation, for the most part, to compressive stress. While the exact stress-strain relations involved in the development of this portion of the Rocky Mountains are not known with certainty, it is, however, certain that an effective component of compressive stress (whether the strain were rotational or non-rotational) has operated at right angles to their long dimension, and so also in a direction at right angles to the postulated possible cross-fractures. Hence any such N.W.-S.E. fractures,

which might otherwise have developed in response to the local tension developed by the torsion, might be prevented from forming by the Rocky Mountain compressive stresses, provided the torsion came at a time when the Cordilleran compressive stresses were still operative. This would not seem an unreasonable assumption since the Rocky Mountain province has been subjected to such stresses during much of Cenozoic time.

But, according to Becker, if faulting takes place because of torsion, the faults should be inclined in the same sense as the thread of a right-handed screw, when the twisting has been clockwise, as it seems to have been in the Lake Basin field case.[1] This would be in consequence of the nature of the strain at or near the surface of the earth. There the direction of elongation should be N.E.-S.W. and fracturing on this principle should occur along lines trending N.W.-S.E. On the other hand, an analysis by the strain-ellipsoid method shows that if a body having two parallel sides, like Daubrée's glass plate, be twisted, the axes of strain on the opposite sides are exactly reversed. In Daubrée's experiment both sets of torsion fractures were about equally developed. This was because the strains developed on the two faces of the glass plate were about equally effective in causing the fracturing of the plate.

For confirmation of these principles, paraffine was molded into strips having the dimensions $12 \times 2 \times \frac{1}{2}$ inches. The ends of these strips were then twisted clockwise as in the Lake Basin case. Each strip snapped apart along a single fracture surface. The fracture in 10 different tests was in accordance with the orientation observed in Montana. In 11 tests it was contrary, the fracturing belonging to the cross set. In every test, without exception, the fracture occurred not far from 45° to the axis of torsion. These tests would seem to indicate that in strips, or plates, of the sort used, neither set of fractures takes real precedence over the other in forming. But in the earth the underside of the paraffine block finds no exact counterpart, and the strain conditions on the upper surface should dominate. Hence, other things being equal, there is greater likelihood that the right-hand-screw fractures

[1] G. F. Becker, "The Torsional Theory of Joints," *Trans. Amer. Inst. Min. Eng.*, XXIV (1894), pp. 130–38.

will be produced. This would be the set at right angles to those actually occurring in the Lake Basin field.

Becker has also stated that, if due to torsion, each master fault will be a reverse fault, and the fissures will gape from the start.[1] Examination of the fracture planes in the paraffine tests revealed the fact that many of them were straight across or, expressed in terms of structural geology, were vertical faults. In others the fault surface was somewhat inclined from the vertical, or was vertical for a portion of the distance and then curved. Where the fault plane was inclined from the vertical the relations were, as Becker has stated, those of a reverse fault. The hanging wall was elevated with respect to the foot wall. The paraffine tests also confirmed Becker's statement that the fissures will gape. This does very well in an experiment where the weight of materials plays no important part. But reverse faults which gape would be a curiosity in the earth. While in the earth, just as in the experiment, the twisting would tend to cause this relation, on the other hand the gravity of the earth, in co-operation with the tension developed by the torsion, should offset this tendency. If the twist developing such a series of parallel faults were accompanied by much tension, downsliding of the blocks should be expected. As there seem to be special grounds for expecting tension, independently of the torsion, in the case under consideration, reverse faulting as the dominant type in this particular strip in Montana would seem unlikely.

Furthermore the strains developed by the doming process above outlined would, in all probability, not be of a very intense sort unless there were also counterpart downwarping north of the Big Horn uplift and a depression of the basin south of the Big Coulee–Hailstone dome to complete the twist. Some depression of the basins seems likely, but the twisting was probably not violent. Hence the fracturing, so far as due to torsion alone, should be not far from vertical, and the tendency toward reverse faulting would be slight. Nevertheless in this connection it is interesting to note that reverse faults actually do occur in one section of the fault belt under consideration.[2] Normal faulting, however, dominates.

[1] G. F. Becker, *op. cit.*, p. 137.

[2] E. T. Hancock, *op. cit.*, p. 140.

From the foregoing inspection of the problem, it would seem clear that this remarkable strip of oblique faults has not been produced by simple torsion alone. The observed facts are at variance in several essential particulars with what the theory of pure torsion should require. The genesis of the faults must have involved in addition other important factors. These are to be sought in an analysis of the larger structural features of the general region, and a consideration of the strains involved in their genesis.

A study of the map of Montana shows that, while the Rocky Mountain chain loses much of its regularity and individual linear character amidst the scattered mountain groups of west central Montana, there is nevertheless a prominent Rocky Mountain trend line which swings sharply eastward in southern Montana, and thence turns south again in the Big Horn range. This particular line of the Rockies thus follows a sigmoidal curve which is perhaps more conspicuous on a small-scale map than a map of a larger scale, for the reason that the details of the minor ranges, if they are too prominent, tend to obscure the larger relations. It was suggested by T. C. Chamberlin that this pronounced bend in the range may have been an important factor in the present problem. The great Lewis overthrust of northern Montana shows that the Glacier National Park region has been transported bodily eastward for at least 15 miles, and possibly much farther.[1] Southward from Glacier National Park the easterly overriding upon the thrust plane gradually diminished, but in any case, even where the faulting has given way to folding as the dominant process, the formation of the Rocky Mountain structure involved an eastward movement of the crumpled and faulted materials. To accomplish the crustal shortening involved in the folding, the main mass of the Big Horn Mountains should have moved eastward to some extent, on the assumption that the deformation was due to thrusting from the Pacific.

The northwestern extremity of the Big Horn anticline, as already stated, extends into the southeastern corner of the area under consideration. Thence westward to the Crazy Mountains

[1] M. R. Campbell, "The Glacier National Park," *U.S. Geol. Survey*, Bull. 600 (1914), p. 12.

the system is poorly developed. This poorly developed tract lies on the border of the eastward-trending portion of the Rocky Mountain belt, which connects its overthrust tract in northern Montana with its south-trending tract in Wyoming and Colorado. Because of its general east-west trend, it was not in a position to be much folded by a thrust from the Pacific, but on the contrary was well placed to receive elongation from the greater eastward thrust of the Rocky Mountains farther to the south. The Big Horn Mountains seem to partake in some measure of both these attitudes, for the southern portion trends with the Rockies in Wyoming and Colorado, while the northern portion veers round to a more westerly trend, and dies down in the Lake Basin district on the very border of the fault belt which, in striking eastward from the Big Coulee–Hailstone dome, is almost tangent to the northern flank of the range.

From these relations it will be seen that, though the deformation on the border of the Lake Basin was limited and gentle, there would naturally have been some eastward movement at the Big Horn end. On the other hand, the Big Coulee–Hailstone dome at the northwesterly end lay on the Great Plains side of the fault belt, in the lee of the less-moved portion of the Rocky Mountain belt, and appears also to be more nearly related to the group of igneous intrusions than to the folded belts, and so should have been less affected than the Big Horn end by the eastward movement. Hence it is inferred that the southern portion of the Lake Basin field, which was most influenced by the Big Horn deformation, was shifted eastward, while the northern portion partook rather more of the relative fixity of the Great Plains province and the area of igneous intrusions. The differential motion involved in this adjustment is not unlike that which produces the oblique crevasses along the margins of glaciers, except that the differential movement was distributed, instead of having a limit at a sharp borderline of slippage such as lies at the junction of the moving glacier with the wall of the valley. No such line of sharp differentiation is of course assignable to the rather broad and gentle movements in the Lake Basin. There may of course have been a concealed longitudinal shear plane deep below the fault

belt, but as the map shows only small oblique faults, this supposition has little or no tangible support and need not be seriously considered here, as the movements already discussed would still be needed to explain the oblique faults. If any underlying longitudinal fault is to be postulated, a group of such faults with distributive action would best fit the case.

On the glacier principle, the southern portion of the district, moving eastward relative to the northern portion, should cause repeated crevasse-like fractures to open along a belt where the strain from the differential motion was greatest. As the south side of the belt moved eastward with respect to the northern side, tension would be developed along N.W.-S.E. lines obliquely across the disturbed zone. The result would be a large number of fracture lines at right angles to the direction of tension, or running N.E. and S.W., as in the upper part of Figure 2. The oblique crevasses in a glacier point upstream as they extend toward the middle of the glacier, or toward the more rapidly moving portion. Hence in this fault problem the fractures should be inclined toward the direction from which the relative motion came. This is just what was observed in the faulted zone of the Lake Basin field. It is then only necessary to suppose that the zone of yielding between the differently moving areas was located where the faults have developed.

Near the eastern end of the fracture belt the downthrow side of nearly all of the faults is toward the northwest. As these are normal faults, most of the fault planes dip to the northwest. On the other hand, near the western end of the belt the downthrow side, and hence also the dip, of the majority of the fault planes is toward the southeast, though the faulting is less regular at this end than at the other. The downslipping in general has thus been from the ends toward the middle of the belt, though the generalization is not so well substantiated in the western half flanking the Big Coulee–Hailstone dome as it is in the more regular eastern half bordering the Big Horn uplift. The dome at either extremity represents a relative upthrust which, if the result of igneous activity beneath, necessarily adds a further element of tension, thus favoring an increase in the number of fractures upon

the flanks of the domes, while at the same time it tends to give the observed slopes to the fault planes.

This peculiar belt of oblique faulting is therefore attributed to the eastward movement of the southern portion of the region relative to the northern, together with the local torsion and incidental tension developed by the doming process.

THE PALEOZOIC SECTION OF THE TOMAH AND SPARTA QUADRANGLES, WISCONSIN[1]

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University of Wisconsin

INTRODUCTION

The Tomah and Sparta quadrangles lie wholly within and on the northeastern edge of the Driftless Area of western Wisconsin. The first-named quadrangle is directly east of the latter. There are 431 square miles in the two areas.

Little geologic work directly relating to the two quadrangles has been published. As parts of the Driftless Area they have received the attention of many of the students who have been concerned with its peculiar problems. Three university theses which directly relate to the whole or parts of the two quadrangles have been written, but none of these has been published.[2] A short paper by W. D. Shipton gives a description of fulgurites[3] found by him near Sparta, and the same author in a second short paper proposed a new formational term for the fine-grained and shaley sandstones which constitute the middle portion of the exposed Cambrian.[4] Other papers which in some degree bear on the geology of the two quadrangles are Ulrich's "Revision of the Paleozoic Systems,"[5] Bassler's "Bibliographic Index of American Ordovician and Silurian Fossils,"[6] in which is given a geologic section

[1] Published by permission of the state geologist of Wisconsin.

[2] R. B. Johns, "The Physiography and Geology of the La Crosse River Valley." Unpublished thesis, University of Wisconsin, 1900. W. D. Shipton, "The Geology of the Sparta Quadrangle." Unpublished thesis, University of Iowa, 1916. W. O. Blanchard, "The Geography of the Tomah-Sparta Quadrangles." Unpublished thesis, University of Wisconsin, 1917.

[3] W. D. Shipton, "A Note on Fulgurites from Sparta," *Proc. Iowa Acad. Sci.*, XXIII (1916), 141.

[4] W. D. Shipton, "A New Stratigraphic Horizon in the Cambrian System of Wisconsin," *ibid.*, pp. 142–45.

[5] E. O. Ulrich, *Bull. Geol. Soc. Amer.*, XXII (1911), Pl. XXVII.

[6] R. S. Bassler, *Bull. 92, United States National Museum*, II (1915), Pl. II.

for Wisconsin, and one of Walcott's papers, in which is defined the geologic section for western Wisconsin as worked out by Ulrich.[1] The latest published work relating to the areas is an abstract of a paper read before the Geological Society of America at the Albany meeting. This paper describes the rock terraces which are such conspicuous features of the surface.[2]

DESCRIPTION OF THE GEOLOGIC SECTION

Only rocks of sedimentary origin are exposed in the Tomah and Sparta quadrangles (Fig. 1). Of these there are two groups: an older, consisting of poorly cemented sandstones and compact, firm dolomites, both of Paleozoic age; and a younger, made up of unconsolidated materials of very late geologic time. With the latter this article is not concerned. The strata of both groups are in essentially undisturbed position.

The Paleozoic strata belong to the Cambrian and Ordovician systems.[3] The exposed thickness aggregates between 700 and 800 feet, while wells which have been drilled to the base of the sedimentary sequence show the presence of an additional thickness of about 350 feet. These unexposed strata are of Cambrian age.

CHARACTER AND ROCKS OF THE PRE-CAMBRIAN FLOOR

The rocks composing the pre-Cambrian floor beneath the Paleozoic sediments are known from deep wells and from exposures some miles to the north. Drillings from a well in Tomah indicate a gneiss of medium texture, composed of clear and milky quartz, pink feldspar, and white mica. The nearest exposures to the north are at Black River Falls, where the pre-Cambrian rocks consist of granites, gneisses, diorites, schists, and iron formation.

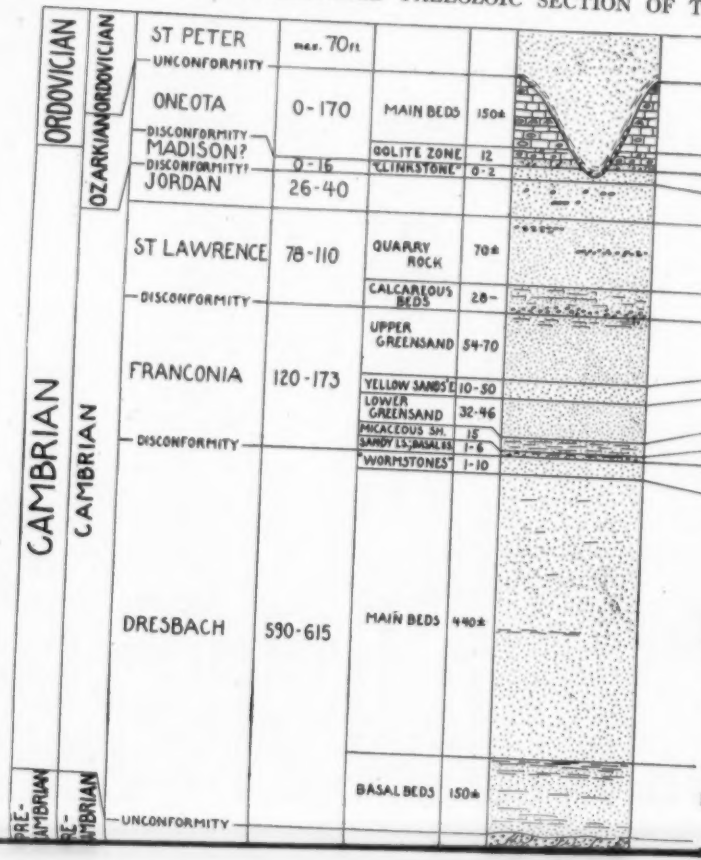
The exposures of the contact between the Paleozoic and pre-Cambrian rocks and the wells in this and adjacent districts which

[1] C. D. Walcott, "Cambrian Geology and Paleontology," *Smithsonian Misc. Coll.*, LVII, No. 13 (1914), 354.

[2] Lawrence Martin, "Rock Terraces of the Driftless Area of Wisconsin," *Bull. Geol. Soc. Amer.*, XXVIII (1917), 148–49.

[3] If the classification of Dr. E. O. Ulrich be followed, there would be three systems represented: Cambrian, Ozarkian, and Ordovician. Fig. 1 shows the groupings of the systems according to the general usage and also according to the proposals of Dr. Ulrich.

GENERALIZED PALEOZOIC SECTION OF THE TOMAH-SPARTA QUADRANGLES, WISCONSIN



St. Peter. Sandstone, fine- to medium-grained, yellow to brown, locally casehardened, bedding heavy to thin, cross-laminated; at base beds of red and green shale resting on residual clay and chert of Oneota.

Oneota (main). Dolomite, medium-grained, gray to drab, bedding medium to thick, many *Cryptozoa*, rare silicified shells, gray, yellow, and red chert nodules.

Oneota (basal). Dolomite and chert as above, both in part oölitic, beds of sandy dolomite and white and yellow medium- and fine-grained dolomitic sandstone with sandstone and dolomitic pebbles and fragments of green shale.

Madison (?). Sandstone, medium- to coarse-grained, yellow to white, heavy-bedded, quartzite at top (the "clinkstone").

Jordan. Sandstone, coarse- to medium-grained, yellow to gray, heavy-bedded, cross-laminated and cross-bedded, scattered sandstone pebbles; not clearly separated from underlying formation.

St. Lawrence (quarry rock). Sandstone, fine-grained, yellow to white, thin-laminated to heavy-bedded, cross-laminated, mud cracks near base and middle, several conglomerate beds with sandstone pebbles, in part edgewise conglomerate, worm holes and fossil impressions abundant in some layers.

St. Lawrence (calc. beds). Sandstone, very fine-grained to shaley, yellow to light brown, very dolomitic in some beds, local thin beds of gray and purple mottled dolomite, fossiliferous; greensand conglomerate at base.

Upper greensand. Sandstone, fine-grained, light yellow to green, thin to medium bedding, cross-laminated, yellow layers very calcareous, some layers very glauconitic, sparingly fossiliferous.

Yellow sandstone. Sandstone, fine-grained, yellow to gray, heavy-bedded.

Lower greensand. Sandstone, fine-grained, gray to green, thin- to thick-bedded, mud-cracked, highly cross-laminated, with short fore-sets, current and wave ripple-marked, glauconitic, fossiliferous.

Micaceous shale. Fine-grained shaley sandstone, micaceous, thin-bedded, light yellow.

Basal beds. Sandy limestone, pink to brown, glauconitic, fossiliferous; sandstone, coarse- to medium-grained, rough-bedded, conglomeratic with sandstone pebbles, cross-laminated.

"Wormstones." Sandstone, coarse- to medium-grained, gray to brown, beds about 1 foot thick composed of firm sandstone, in which are large vertical worm holes ("wormstones") alternating with thinner beds of soft white sandstone with limonite and siliceous concretions (nodular layers).

Main beds. Sandstone, medium- to coarse-grained, light yellow to gray, bedding medium to heavy, wave and current ripple marks, rare mud cracks, cross-laminated, thin laminae of green shale, possibly a local shale bed a few feet thick about 250 feet below top, local limonite cemented beds. Lower 150 feet known only in wells.

Basal beds. Sandstone as above with beds of red, green, and black sandy shale, shale beds of variable thickness up to perhaps half a dozen feet. Known only in wells.

have been drilled to this contact suggest that the pre-Cambrian lands had been reduced to slight relief before the deposition of the Cambrian sands.

THE CAMBRIAN SYSTEM

Sandstones compose nearly the whole of the Cambrian rocks of the two quadrangles. Some of the finer-grained sandstones have been called shales, but were most of such in association with true shales they quite certainly would be called sandstones. True clay shales are present only as thin laminae and lenses. Dolomite and dolomitic sandstones of local and horizontal distribution also occur. The basal strata of those exposed consist almost wholly of quartz sandstones. The sands are commonly clean and well sorted. The higher Cambrian strata are also largely composed of quartz sands, but some portions contain an abundance of greensand. The top of the Cambrian is quite sharply defined from the base of the Ordovician by the rather general occurrence near the contact of quartzite-like gray sandstones and by the great differences between the dolomite of the basal Ordovician and the sandstone of the highest member of the Cambrian.

Four Cambrian formations are exposed. These, in ascending order, are (1) the Dresbach sandstones, (2) the Franconia glauconitic and shaley sandstones, (3) the St. Lawrence sandstones and dolomitic shales with occasional dolomite layers, and (4) the Jordan sandstones. There is a possibility that a fifth Cambrian formation is present, since at the top of the Cambrian sequence there are a few feet of strata which somewhat resemble the Madison sandstone. The 350 feet of unexposed strata may contain the Eau Claire and Mount Simon formations of Dr. Ulrich's section. The total thickness of the Cambrian is about 900 feet (Fig. 2).

The Cambrian sediments were deposited in shallow water above wave-base. This is proved by the abundant occurrence of both wave and current ripple mark and the wonderful development of cross-lamination in which there are steep fore-sets up to 50 feet in length. Mud cracks, which are present in at least three horizons, prove that at times the sediments were exposed to the drying effects of the sun. The rounding, sorting, and cross-lamination of some of the sands suggest local eolian deposition.

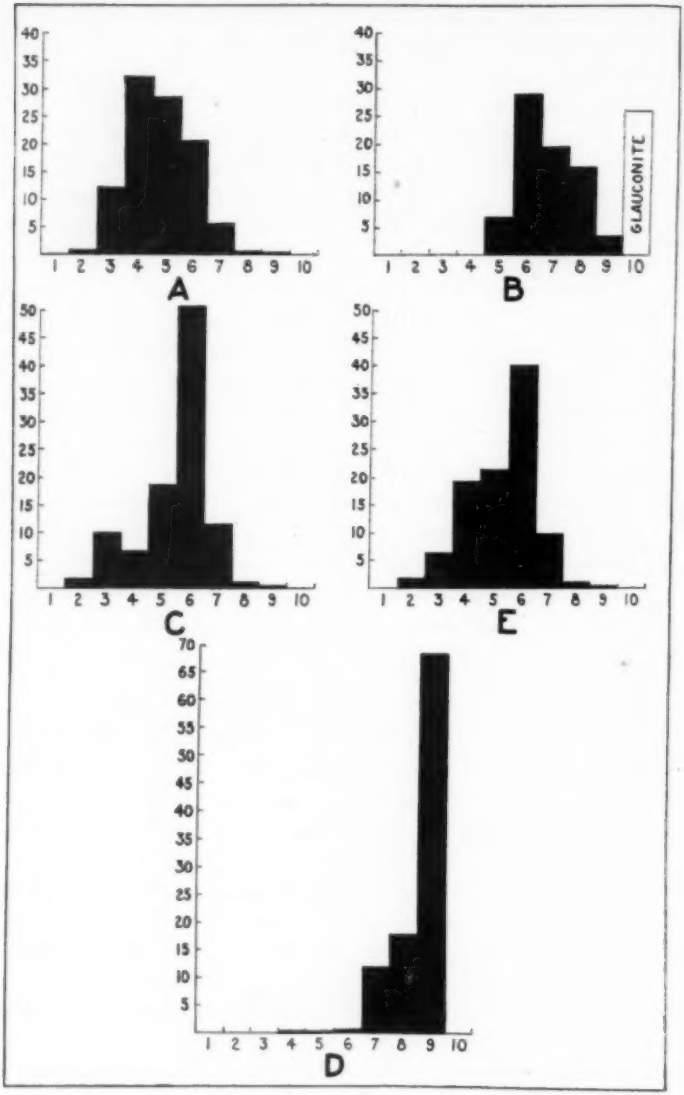


FIG. 2.—Mechanical analyses of characteristic sands (for description see opposite page).

EXPLANATION OF THE DIAGRAMS OF FIG. 2

The ordinates represent percentages by weight, the sum of all the rectangles in each diagram totaling 100 per cent. Abscissae represent the dimensions of the quantity indicated by the rectangle immediately above it. These for convenience are numbered 1 to 10, the dimensions corresponding to the numbers being as given below. The analyses were made with Tyler Standard Screen Scale Testing sieves:

1. Between 1.168 and .833 mm.
2. Between .833 and .589 mm.
3. Between .589 and .417 mm.
4. Between .417 and .295 mm.
5. Between .295 and .208 mm.
6. Between .208 and .147 mm.
7. Between .147 and .104 mm.
8. Between .104 and .074 mm.
9. Smaller than .074 mm.
10. This does not represent dimensions, but material which is different from the main body of the sand. The loss in sifting (generally less than 1 per cent) has been added to No. 9, as the finest grades suffer the greatest loss.

A. Dresbach sandstone, Tunnel City, 65 feet from the top of formation.

	Percentage	
1.	0.036,	spherical grains of transparent quartz.
2.	0.755,	well-rounded grains of transparent quartz.
3.	12.080,	transparent quartz, most grains well rounded, a few subangular.
4.	32.120,	transparent quartz, grains well rounded to subangular.
5.	28.270,	transparent quartz, grains well rounded to subangular, a few grains angular.
6.	20.460,	transparent quartz, estimated 10 per cent angular, 25 per cent well rounded.
7.	5.600,	transparent quartz, a few grains well rounded, most subangular to angular.
8.	0.312,	transparent quartz, nearly all grains sharply angular.
9.	0.367,	transparent quartz, grains angular.

This sand is of beach origin.

B. Lower greensand of the Franconia formation, collected at Boscobel on the Wisconsin River, south of the quadrangles.

	Percentage
1.	0.00.
2.	0.00.
3.	0.00.
4.	0.00.

Percentage

5. 6.83, transparent quartz, grains subangular to angular.
6. 28.80, essentially no rounding.
7. 19.27, no rounding, a little dolomite.
8. 15.71, as No. 7.
9. 3.47, as No. 7, with about 10 per cent dolomite.
10. 25.84, this rectangle represents the glauconite present in the sample.

This sand was deposited some distance from the belt of constant wave-wash as shown by its fineness and little rounding.

C. Fine-grained sandstone from near base of the Jordan, Jeff Davis Rock, Tomah quadrangle.

Percentage

1. 0.00.
2. 1.78, transparent quartz, grains highly spherical and pitted.
3. 10.00, transparent quartz, high sphericity, grains pitted.
4. 6.45, transparent quartz, high sphericity, grains pitted, estimated 5 per cent subangular.
5. 18.52, transparent quartz, with a few grains of limonite, grains well rounded and pitted, 5 per cent subangular.
6. 50.50, as No. 5.
7. 11.29, transparent quartz, well rounded with a few angular grains.
8. 1.06, transparent quartz, 60 per cent subangular to angular.
9. 0.40, transparent quartz, with a little clay, and dolomite, about 5 per cent rounded, about 10 per cent aggregates of finely divided quartz.

The assortment, rounding, and cross-lamination of this sand suggest wind deposition.

D. St. Lawrence sandstone, 2 miles southeast of Norwalk, Wis., 50 feet below base of Oneota. Contains marine fossils.

Percentage

1. 0.00.
2. 0.00.
3. 0.00.
4. 0.40, transparent quartz, grains rounded.
5. 0.36, transparent quartz, rounded and subangular grains, estimated 10 per cent muscovite flakes.
6. 0.60, as No. 5.
7. 12.00, transparent quartz, angular grains, occasional muscovite flakes and limonite grains, a little dolomite.
8. 17.92, transparent quartz, nearly all grains angular.
9. 68.72, transparent quartz, 75 per cent aggregates, no rounding whatever.

The last rectangle does not express the actual facts as it is composed of grains varying from .074 mm. in diameter to dimensions fully one one-hundredth of that dimension. This sand was deposited beyond the zone of constant wave-wash.

E. St. Peter sandstone, Cashton, on the southwestern edge of the Sparta quadrangle, estimated 30 feet above the base.

	Percentage
1.	0.00.
2.	1.80, transparent quartz, high sphericity.
3.	6.28, as No. 2.
4.	19.21, as No. 3.
5.	21.42, transparent quartz with a few limonite grains and fragments of calcite, most well rounded, but numerous subangular grains.
6.	40.00, transparent quartz with a few grains of limonite, well rounded, estimated 25 per cent subangular.
7.	9.81, as No. 6, 50–60 per cent subangular, 10 per cent angular with no rounding.
8.	1.13, transparent quartz, 75 per cent sharply angular, rest subangular.
9.	0.352, transparent quartz, with rare garnet grains, essentially all angular.

The assortment, rounding, and cross-lamination of this sand suggest wind deposition.

Save for local and horizonal exceptions, the Cambrian sandstones are poorly cemented. Most of the beds crumble on slight exposure and in numerous places fresh rock may be crushed to sand with the hands.

THE DRESBACH FORMATION

The type locality for the Dresbach formation, first called the "Dresbach sand rock," is at Dresbach, Winona County, Minnesota, 18 miles west of this area. At Dresbach the character and sequence of the strata appear to be quite similar to what they are in these quadrangles, although lower shaley strata are present there which have not been differentiated in this area.[1] What is known of the unexposed Cambrian strata of these two quadrangles is included in the description of the Dresbach formation, although it is quite possible that these strata contain the Eau Claire and Mount Simon formations.

The Dresbach strata immediately underlie the lower lands of the two quadrangles. Where the formation has been completely uncovered through the removal of the higher formations, there has

[1] N. H. Winchell, *Minn. Geol. and Nat. Hist. Surv., Final Rept.*, II (1888), xxi.

developed a gently rounded, discontinuously terraced topography. Along the deeper valleys, in such places where the overlying formation has not been completely removed, the upper strata of the Dresbach rise from steep slopes to form coalescing tower-like cliffs or conical buttes.

Characteristics.—The exposed strata of the Dresbach consist of poorly cemented quartz sandstones of which the grains are clean and well rounded. In most of the beds the assortment is extremely good. Interlaminated with the exposed sandstones are thin lenses (up to about a centimeter in thickness) of green sandy shale. Well records show the presence in the unexposed strata of greenish, bluish, and reddish shale. Most of these occur about 450 feet below the top of the Dresbach and may represent a part of the Eau Claire formation. The sands are generally poorly cemented, and very few layers are sufficiently firm for use in construction. The colors vary from gray to yellow. "Iron rocks"—sands cemented by hydrous iron oxide—are locally present in considerable abundance, but are not characteristic of any horizon.

The strata are not continuous for long distances, and with the exception of worm-perforated beds, which are prominent in the upper horizons, it has not been found possible to identify any portion beyond the limits of a single exposure. In the field these upper strata were known as the "wormstones." Cross-lamination at variable inclinations with variable directions is present in nearly every outcrop. The fore-sets are generally short, 5 to 6 feet being the average maximum, but in an outlier near the village of Rockland there are fore-sets at angles of 15° to 20° which exceed 50 feet in length. The inclination of the long fore-set cross-lamination at Rockland is nearly due east. In a number of cases the cross-lamination has the appearance of having been produced by wind deposition. The nature of the Dresbach sediments was not favorable for the development of mud cracks, but such are present just east of Rockland in a horizon about 100 feet below the top of the formation.

The thickness of the exposed Dresbach is about 300 feet. Well records show that from 590 to 615 feet are present from the base of the Franconia formation to the pre-Cambrian floor.

Except for worm tubes, of which there appear to be at least two varieties, fossils have not been observed in the Dresbach sandstones of the two quadrangles. The most common worm tubes are of the Scolithus type. They are extremely abundant in the upper beds.

Conditions of origin.—The sediments of the Dresbach formation were accumulated in shallow water above wave-base or above water-level. It does not seem probable that at any time the waters attained sufficient depth to remove the sands from the wash of the waves. The possible eolian cross-lamination and certainly the mud cracks prove that at times the sites of deposition were above water-level. The writers' conception of the conditions of deposition is that of an extensive sand flat, of which parts may have been continuously underneath the water, other parts were exposed at low tide, while other areas—sand islands, bars, etc., thrown up by the waves and piled higher by the winds, the different environments shifting more or less from time to time—were above water-level. These conditions granted, the clean washing of the sands, the local thin laminae of shale, the presence of mud cracking, the abundance of both wave and current ripple mark, the excellent sorting of the sands in most of the beds and their quite perfect rounding in some beds, the great development of cross-lamination of which some appears to be eolian, the variable and lenticular character of Dresbach bedding, and the general absence of fossils follow as natural consequences, and it is difficult to conceive how all these characters could have developed on an extensive scale under any other conditions.

THE FRANCONIA FORMATION

The Franconia formation was defined by Berkey[1] without its upper and lower limits being stated. In some of the publications of the United States Geological Survey the strata which constitute the Franconia formation appear to have been included in the St. Lawrence,[2] which as thus defined includes two stratigraphic

[1] C. P. Berkey, "Geology of the St. Croix Dalles," *Amer. Geol.*, XX (1897), 373, 377.

[2] G. W. Hall, O. E. Meinzer, and M. L. Fuller, "Geology and Underground Waters of Southern Minnesota," *Water Supply Paper No. 256, U.S. Geol. Surv.* (1911), pp. 63–68; W. H. Morton and others, "Underground Water Resources of Iowa," *Water Supply Paper No. 293* (1912), Pl. II, p. 65.

units of decidedly different lithology which are separated by a quite generally well-exposed greensand conglomerate. The strata, which in this article are referred to the Franconia formation, are included between the top of the Dresbach and the base of this greensand conglomerate.

The Franconia strata cap divides over considerable portions of the northern halves of the two quadrangles. These have a rolling, more or less terraced, topography with mammillary knolls. Where overlain by higher strata the Franconia makes a terraced slope on which at least two terraces are almost everywhere present.

Relations to the Dresbach formation.—There is apparent conformity between the Franconia and Dresbach formations; but the fact that there are some differences in the sequence at the top of the Dresbach and the presence at the top of that formation of what may be small erosion channels suggest that the contact of the two formations is one of disconformity, with the possibility that the lower was eroded before the deposition of the upper.

Subdivisions and their characteristics.—The greater portion of the Franconia formation consists of fine-grained quartz and glauconitic sandstones. The clay content is limited to thin shale partings. A few beds contain small percentages of dolomite and near the base there is a sandy limestone. There are few beds in the formation which do not contain some greensand.

The thickness of the Franconia varies from 120 to 173 feet. The thickest sections are in the northern halves of the two quadrangles, although a well drilled at Cashton, just off the southeast corner of the Sparta quadrangle, indicates a thickness of about 170 feet. The thinnest section, 120 feet, was measured near the center of the Sparta quadrangle.

It is possible to divide the Franconia formation into five members, which in ascending sequence are: (1) the basal sandstone and overlying calcareous layer, (2) the micaceous shale, (3) the lower greensand, (4) the yellow sandstone, and (5) the upper greensand. These five members are continuous over the whole of the two quadrangles and for considerable distances beyond their limits.

1. The basal sandstone is roughly and irregularly bedded and is everywhere cross-laminated. Colors vary from gray to brown with

some layers so rich in greensand as to have a greenish-black color. Sorting is extremely poor. Fossil fragments, of which every one appears to have been washed about for a considerable time before final deposition, are locally very abundant. The thickness varies from 1 to 6 feet.

The overlying calcareous layer varies from a calcareous sandstone to a nearly pure limestone. The rock has a brownish-pink to red color and is generally cross-laminated with short fore-sets to the laminations. These have no constant direction of inclination. Small articulate brachiopods are present locally in considerable abundance. The thickness varies from nothing to about 4 feet.

2. The micaceous shale is really a fine-grained, thin, laminated sandstone. The colors vary from gray to yellow. The sandstone is composed chiefly of quartz with some of the bedding and lamination planes containing an abundance of thin flakes of white and colorless mica. Some beds are current-ripple marked and others have the bedding planes abundantly covered with fucoidal markings. Fossils, all of which appear to have been washed about before deposition, are quite abundant. The thickness varies around 15 feet.

3. The lower greensand is composed of thin laminated glauconitic and quartz sandstones. Greensand is present in essentially every bed; the proportion varies widely. Some thin layers are fully 75 per cent greensand, many beds have more than 20 per cent, while in others its occurrence is limited to occasional grains. Some of the strata are evenly bedded, but more commonly the bedding is decidedly irregular and lenticular. Cross-lamination is present throughout. The fore-sets are generally short and apparently have no uniform direction of inclination. Near the middle are mud-cracked layers which have been seen in nearly every exposure of the member. Both wave and current ripple mark, the latter by far the more abundant, are present in every exposure of any size. Fossils, all of which appear to have been washed about before final deposition, are common in many beds. The thickness varies around 40 feet.

4. The yellow sandstone member is composed of thick-bedded, horizontal and cross-laminated yellow and gray sandstone. Greensand is present in some layers. Transverse worm tubes are the

only fossils which have been seen. The thickness varies from 40 to 50 feet.

5. The upper greensand is similar in its characteristics to the lower greensand, but fossils are not nearly so common. Near the top are thin layers (1 inch maximum thickness) of very dolomitic, fine-grained, yellow sandstone interbedded with highly glauconitic medium-grained sandstone. Iron pyrite has been observed locally. The thickness varies from 54 to 70 feet.

Conditions of origin.—The Franconia sediments are wholly of marine origin, a conclusion proved by the quite general abundance of marine fossils. The cross-lamination everywhere present shows that the deposition took place above wave-base. The much smaller dimensions of the grains of sand and the higher percentages of angular grains suggest that the waters were considerably deeper than were those in which the Dresbach sediments of these quadrangles were deposited. The mud cracks in the lower greensand prove that at times during the deposition of that member several hundred square miles of the two quadrangles lay above water-level. The writers believe that somewhat similar shore conditions obtained during Franconia time as during Dresbach, with the difference that the Franconia sediments were deposited somewhat farther from land influences. Any interpretation must take into consideration the occurrence and abundance of greensand. This evidence has not been thoroughly evaluated, but nothing has been discovered which is not in harmony with the foregoing interpretation.

THE ST. LAWRENCE FORMATION

The St. Lawrence formation was defined by N. H. Winchell as the St. Lawrence limestone.[1] Its limitations were not definitely given because they were not known. The stratigraphic boundaries as they exist in western Wisconsin were worked out by Ulrich, and in this article the term is used with the significance given it by him. The strata of the two quadrangles which are referred to the St. Lawrence by the writers were designated the Sparta shales by Shipton on the supposition that they represented an

[1] N. H. Winchell, *Minn. Geol. and Nat. Hist. Surv., Second Ann. Rept.* (1874), pp. 152–55; *Fourth Ann. Rept.* (1876), pp. 32–34.

undescribed stratigraphic unit.[1] This supposition does not appear to be correct.

Where the St. Lawrence is not overlain by higher strata there develops a rolling topography of gentle outlines. Where higher strata are present there is a gently sloping surface on which relatively resistant strata near the middle of the formation give rise to discontinuous terraces. Quite commonly the upper beds of the St. Lawrence form the basal portions of the higher tier of cliffs.

Relations to the Franconia formation.—At all places where the contact between the Franconia and the St. Lawrence has been seen there is present an edgewise conglomerate composed of pebbles derived from the upper greensand member of the Franconia. These pebbles appear to have been indurated before their deposition, thus indicating the exposure and erosion of Franconia rocks at the beginning of the St. Lawrence deposition. If such erosion has occurred, as appears quite probable, it follows that the two formations are separated by a disconformity. The variation in thickness of the Franconia is in harmony with this conclusion.

Characteristics.—In the exposures of the Tomah and Sparta quadrangles the St. Lawrence formation consists largely of sandstones. Some of the beds of the lower half are more or less dolomitic and shaley and others contain small quantities of greensand. Farther to the southeast in the Wisconsin Valley the dolomite content is greater, and one member of the formation is a dolomite.

It is possible to divide the St. Lawrence into two members: a lower, composed of shaley and fine-grained, light-yellow to light-brown sandstone in which there are some dolomitic layers with local lenses (1 foot maximum thickness) of gray- and purple-spotted dolomite and also a little greensand, and an upper, consisting of fine-grained yellow sandstones in which are several layers (6 inches to 4 feet) of conglomerate composed of fine-grained yellow sandstone pebbles of lenticular shapes in a matrix of yellow sandstone of coarser grain. The pebbles are commonly in horizontal position, but a conglomerate near the middle of the formation has them in edgewise position with inclinations varying to nearly vertical. The

[1] W. D. Shipton, "A New Stratigraphic Horizon in the Cambrian System of Wisconsin," *Proc. Iowa Acad. Sci.*, XXIII (1916), 142–45.

sandstones are generally thin-laminated and quite regularly bedded. In some of the layers, particularly those in the upper member, cross-lamination is present to a high degree. The angles of inclination are generally low and of variable direction; but inclinations of southerly direction appear to be the more common. The thickness varies from 78 to 110 feet.

Fossils are extremely abundant in some layers, most of them being trilobites. One of the locally developed dolomitic layers of the lower member contains numerous brachiopods which are identical with, or closely related to, *Billingsella coloradoensis* (Shumard). The broken condition of the trilobites indicates that they were washed about by waves and currents before their final deposition.

Conditions of origin.—The St. Lawrence strata are of marine origin, and the sediments composing them were deposited in shallow water. Some beds were deposited under conditions which permitted the development of mud cracks, such having been found near the base of the formation on the northeastern edge of the Tomah quadrangle and near the middle of the lower member on the Wisconsin River. The numerous bands of conglomerate prove waters sufficiently shallow for the transportation of good-sized pebbles over extensive areas; presumably these were derived from the shores and carried out to deeper waters. They may possibly indicate backward and forward migration of the shore line. It is believed that the broad sand-flat conditions postulated for the times of the preceding formations were still existent, and that the St. Lawrence sediments indicate somewhat greater depths of water and greater distances from land conditions than obtained during the deposition of the Dresbach sediments of the two quadrangles.

THE JORDAN FORMATION

Succeeding the fine-grained sandstones of the upper St. Lawrence are sandstones which are correlated with the Jordan formation of Minnesota, the writers using that term in the sense defined by Ulrich in the paper by Walcott. Throughout the two quadrangles the sandstones referred to this formation in large part make the upper tier of cliffs.

Relations to the St. Lawrence formation.—In many places it is extremely difficult to locate the surface of division between the St. Lawrence and Jordan formations. Locally the strata assigned to the Jordan begin with a long, fore-set, cross-laminated stratum which in comparison with the more horizontally laminated St. Lawrence makes the contact quite conspicuous. In some exposures a thin layer of conglomerate marks the contact. In their larger relations the two groups of rocks are quite different, the bedding of the Jordan being much more irregular and the sands more coarse than obtain in the St. Lawrence. The writers have observed no decisive evidence in this area that the St. Lawrence strata were eroded before the deposition of the Jordan.

Characteristics.—The Jordan formation in these two quadrangles consists wholly of sandstone. The textures vary from coarse to fine and the colors from gray to light brown. The sorting is generally not good. Some beds contain an abundance of fine-grained sandstone pebbles. A characteristic feature is the presence of calcareous concretions with diameters varying from a fraction of an inch to about 2 inches. The bedding is massive and extremely irregular. Cross-lamination and cross-bedding are present throughout, some of the fore-sets being up to 50 feet in length and having angles of inclination for such lengths up to 25°. Directions vary, but the writers' observations indicate a dominance of inclination in a southerly direction. No fossils have been observed in this formation in either of the two quadrangles. The thickness varies from about 20 to about 40 feet.

Conditions of origin.—There is no known evidence in either of the two quadrangles to indicate that the Jordan sandstone is of marine origin. Parts of it appear to have been deposited by the wind. To the writers it appears probable that the formation represents the emergent deposits consequent upon the complete withdrawal of the waters from the sand flats postulated for the times of the preceding formations.

THE MADISON (?) FORMATION

Overlying the sandstones which have been identified as belonging to the Jordan are other sandstones which in some respects resemble those of the Madison formation. These sandstones are

better stratified than are those immediately below. They are also usually more or less dolomitic, and at or near the top there is quite generally a hard quartzite-like sandstone to which the field name of "clinkstone" was given. Up to the present these sandstones have yielded no fossils other than worm borings which resemble those found in the typical Madison sandstone. The thickness varies from 2 to about 20 feet.

If these sandstones are really of Madison age it is probable that an erosion interval occurred between the deposition of the Jordan and the Madison. The decisive evidence for such an interval has not been found in these quadrangles, although suggested by the considerable variation in the thickness of the Jordan. Such variation in thickness, however, is readily explained through inequality of deposition, which is a rather usual condition in sandstone deposits. Near Madison the Mendota dolomite is said by Ulrich to hold a stratigraphic position between the Madison and Jordan formations.[1] If this be correct and these sandstones are really of Madison age, there is little doubt of the presence of a disconformity.

ORDOVICIAN SYSTEM

INTRODUCTION

Only two formations of the Ordovician system are present within the two quadrangles. These are the Oneota dolomite (in the arrangement of the systems of Dr. Ulrich the Oneota and the Madison are referred to his Ozarkian system) and the St. Peter sandstone, each markedly different from the other in character, origin, and distribution. The two formations are separated from each other by a decided disconformity of marked relief.

THE ONEOTA FORMATION

The Oneota formation underlies the higher uplands and, except for small outliers, is largely confined to the southern halves of the two quadrangles. These upland areas have gentle outlines and slope with slight inclination in a southwesterly direction.

[1] E. O. Ulrich, "Correlations by Displacements of the Strandline, etc.," *Bull. Geol. Soc. Amer.*, XXVII (1916), 460.

The Oneota is quite commonly considered the lower member of the Prairie du Chien formation. In the older nomenclature it constituted one of the members of the Lower Magnesian group.

Relations to underlying strata.—There is essential parallelism between the beds of the Oneota and underlying strata, but it is believed that the latter were eroded before the deposition of the former. The basal bed of the Oneota is quite commonly a conglomerate, and mud cracking is not rare in the associated clayey beds. The quartzite-like beds—the "clinkstones"—in the upper portion of the Madison (?) may be a case of pre-Oneota case-hardening resulting from exposure before Oneota deposition. Near Madison bowlders of a quite similar quartzite are present in the basal Oneota, suggesting that the foregoing is a possibility. The thickness of the underlying sandstones varies from place to place, and the upper surface of these sandstones suggests erosion before the deposition of the Oneota.

Characteristics.—The Oneota formation consists of firm and compact dolomites in regular beds. Colors vary from gray to drab. Some of the lower beds are oölitic. The basal beds are somewhat sandy, and a conglomerate of dolomite and sandstone pebbles in a sandy dolomite matrix is quite commonly present at the base. This conglomerate and some of the immediately overlying sandstone beds contain flakes of green shale. The sandy beds persist through about a dozen feet of strata. Quite commonly the sandy beds are so firmly cemented as to form quartzite. A few feet above the base there is a rather persistent bed of fine-grained white sandstone which locally is firmly cemented to form a white quartzite. Much gray, blue, and yellow chert is present throughout, and some beds contain vast quantities. The chert of the oölitic layers is also oölitic. The dolomite contains many small cavities, some of which are lined with white, yellow, and amethystine quartz.

The maximum thickness of the Oneota in these areas is not believed to exceed 170 feet.

The most common fossils of the Oneota formation are irregular masses of *Cryptozoa*. These are abundantly present as isolated individuals and more rarely as reeflike masses, one of the latter

quite commonly being present about 30 feet above the base. In fully half of the occurrences they are composed of chert. Other common fossils are small cephalopods, low-spired gastropods, and shells of a chiton-like organism. These are generally poorly preserved, casts and molds being the only forms which have been observed, and the writers—the chiton-like form excepted—have found them only in the chert. The writers have found no fossils composed of dolomite except those of *Cryptozoa*.

Conditions of origin.—The strata of the Oneota formation are wholly of marine origin. They are not the deposits of deep water, but in large part appear to have been deposited below wave-base.

THE ST. PETER FORMATION

The St. Peter sandstone occurs only as small patches which fill erosion depressions in the Oneota. None has been discovered over the northern half of the area. The most extensive occurrence is in the southeastern corner of the Sparta and the adjacent part of the Tomah quadrangle. Residual float from the St. Peter is quite abundantly present over those parts of the uplands which are underlain by the Oneota.

Relations to underlying formations.—The most striking feature of the St. Peter formation is the relief of the disconformity which marks its base. The stratigraphic position of the St. Peter in this region is above the Shakopee formation; but that formation, if deposited over these two quadrangles, was removed before St. Peter deposition, so that the St. Peter rests on the Oneota, except in one exposure, where it was found to rest on the Jordan, thus giving to the surface of disconformity a stratigraphic relief of fully 200 feet.

Characteristics.—The St. Peter formation consists of loose, friable, yellow to brown, fine- to medium-grained sandstone with a variable thickness of red and green non-calcareous shales and fine-grained shaley yellow sandstones in the basal portions. At every place where the base of the stratified St. Peter was observed it rests on a residuum of red clay and chert which is altogether without stratification. This residuum was derived from the weathering of the Oneota and possibly higher formations. In this article this unstratified material is assigned to the St. Peter, although it developed during the time of erosion which intervened in this area

between the Oneota and the St. Peter and thus might be considered a distinct formation. Some of the sandstones are locally so case-hardened as to resemble quartzite, and these form a residual float over the surface of the Oneota. In many cases the sandstones are so little cemented as to be quarried for sand. Except for the basal layers, the sands are clean, well sorted, and well rounded. A large proportion of the grains are of high sphericity. The strata immediately above the residuum are fairly well bedded. Higher strata have all degrees of cross-lamination and cross-bedding.

The known thickness of the St. Peter in this area does not exceed 70 feet. No fossils have been found in the St. Peter sandstones of this area or, for that matter, in any part of Wisconsin known to the writers. In eastern Minnesota the St. Peter has yielded fossils.[1]

Conditions of origin.—While all the facts relating to the origin of the St. Peter have not yet been completely evaluated and more data are being collected, it does not appear probable to the writers that any part of the St. Peter sandstones in either of the two quadrangles is of marine origin. The basal portions are certainly of residual origin and as this residuum extends over the tops of the St. Peter hills it proves the absence of marine-wave wash during the deposition of all material up to the tops of these hills. The shales and sandstones immediately overlying the basal residuum appear to be of stream deposition. The higher, clean, cross-laminated sands have characteristics which suggest their modification and deposition by the wind.

CONCLUSION

With the St. Peter formation the Paleozoic section of the Sparta and Tomah quadrangles is concluded. That other Ordovician and also Silurian formations once extended over this region is strongly suggested, if not proved, by the ragged edges of strata of these two systems which are found at comparatively short distances to the south and west. It is possible that formations younger than the Silurian were once present; but, if so, evidence of their former existence has not been discovered.

[1] F. W. Sardeson, *Bull. Minn. Acad. Nat. Sci.*, IV, No. 1 (1896), pp. 64–88.

THE HORIZON OF THE MARINE JURASSIC OF UTAH

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Some time ago the writer, during the course of a reconnaissance in southern Utah, made a small collection of fossils from marine beds near the base of what is quite probably the McElmo formation. These were collected about a half-mile southwest of Teasdale (Teardale on the Fish Lake reconnaissance topographic sheet of the United States Geological Survey), probably in section 20,

FIG. 1.—Contact of thin-bedded marine Jurassic limestone on white cross-bedded sandstone of La Plata group. One-half mile southwest of Teasdale, Utah. (Contact at black line.)

T. 29 S., R. 4 E. At the point where the fossils were collected the exposures consisted of about 100 feet of white massive cross-bedded sandstone, taken to be the top of the La Plata, above which were a few feet of thin-bedded shaly limestones, constituting the fossil-bearing horizon (Fig. 1). On account of the inaccessibility of the slopes and the very limited time available, no detailed section was measured at this point.

The writer, however, measured a detailed section near the mouth of Cedar Canyon, about 6 miles due east of Loa, along the west base of Thousand Lake Mountain, just east of the fault that is reported by Dutton[1] to form the west scarp of that mountain. The section follows. Figure 2 shows the beds in the upper part of the section.

SECTION AT MOUTH OF CEDAR CANYON, 6 MILES EAST OF LOA

No.	Feet	
29	....	Talus from cliffs of overlying lava.
28	375+	Alternating green and red sandy shales with occasional gypsum beds.
27	40	Covered slope, abundant gypsum fragments, probably gypsum.
26	100	Gypsum with thin clay seams.
25	10	Drab shale, more massive than No. 24, forms ledge.
24	22	Thin-bedded drab shale in slope.
23	50	Calcareous gray shale, in cliff, weathers with rounded surfaces.
22	3	Slightly argillaceous notably cross-bedded limestone.
21	11	Covered slope; digging shows red and gray clay.
20	5	Dense thin-bedded calcareous shale or argillaceous limestone, forms bench.
19	32	Thin-bedded calcareous shale or argillaceous limestone, forms slopes.
18	1	Brown, sandy, porous limestone.
17	4	Greenish gypsum.
16	5	Green argillaceous sandstone.
15	5	Covered slope.
14	30	Gypsum.
13	25	Covered slope, probably red shale.
12	1	Gray limestone.
11	3	Thin-bedded drab shale.
10	5.	Very light gray limestone.
9	16	Fairly well-bedded greenish, argillaceous sandstone.
8	10	Covered, probably shale.
7	20	Fissile red-brown shale, in a bench with marked re-entrant angles.
6	36	Thin-bedded drab shale.
5	6	Gray limestone, with thin shale near middle, fossiliferous.
4	1	Greenish sandy shale.
3	8	Thin-bedded drab limestone, slightly cross-bedded.
2	35	Tan-colored, well-bedded argillaceous sandstone.
1	130	White cross-bedded sandstone.
	989	

[1] C. E. Dutton, "Report on the Geology of the High Plateaus of Utah," 1880.

In this section, Nos. 1 and probably 2 are thought to be La Plata. No. 6 is almost certainly the same horizon from which the Teasdale collection of fossils was made. It is perhaps 10 miles or less from Cedar Canyon southeast to Teasdale.

The fossils were submitted to Dr. T. W. Stanton, of the United States Geological Survey, who lists them as follows: *Pentacrinus whitei* Clark; *Camptonectes platessiformis* White; *Trigonia quadrangularis* Hall and Whitfield; small undescribed gastropods.

Dr. Stanton[1] says, "These fossils show close relationship with the Sundance fauna, but there have been different opinions concerning the exact position of the bed containing them with reference

FIG. 2.—White, red, and green sandy shale and gypsum above marine Jurassic limestone, head of Cedar Canyon, 6 miles east of Loa, on west slope of Thousand Lake Mountain, Utah.

to the La Plata. C. T. Lupton, who observed the same fossiliferous horizon, included it in the McElmo and agreed with you in considering the top of the underlying sandstone as the top of the La Plata.[2] W. B. Emery, who has had the advantage of field work in northeastern Arizona and northwestern New Mexico as well as southern Utah, thinks that this fossiliferous Jurassic limestone represents the Todilto formation which is near the middle of the La Plata group according to Gregory's stratigraphy in *Professional Paper 93*.

[1] Personal communication.

[2] *U.S. Geol. Surv., Bull. 541*, p. 125.

You will find his discussion of the section in a paper on the Green River Desert section, Utah."[1]

The earliest reference to fossiliferous beds at this horizon in this locality that has come under the notice of the writer is by Gilbert,[2] who, in describing the Flaming Gorge formation, says: "In the immediate vicinity of the Henry Mountains it varies little except in color from summit to base, but in other localities not far distant it is interrupted near the base by thick beds of gypsum and gypsiferous clays, and by a sectile, fossiliferous limestone." Gilbert's Vermilion Cliff and Gray Cliff sandstones in this locality have been generally supposed to represent the two major divisions of the La Plata group, described by Gregory[3] in the Navajo country as the Wingate and Navajo sandstones respectively; and although Cross[4] interprets the Vermilion Cliff of the older writers to be the upper part, at least, of the present Dolores formation, anyone who has studied the detailed section given by Gilbert in the identical localities from which he describes them cannot help being certain that his upper Shinarump shales are Dolores, and that his Vermilion Cliff sandstone includes the base of the La Plata and probably does not include any of the Dolores. Likewise Gilbert's Gray Cliff is La Plata, and his Flaming Gorge is in part, and probably in totality, the equivalent of the McElmo formation of more recent writers.

The present writer has studied these formations in some detail in the region described by Gilbert, particularly along Water Pocket Canyon and on the Water Pocket Flexure. Here the total thickness of the Vermilion Cliff and Gray Cliff together is estimated (not measured) as not less than 1,500 feet. Near the contact between them is about 100 feet of shaly red sandstone, less resistant than the material above and below, and this is believed by the writer to correspond to Gregory's Todilto beds. The general

[1] *Amer. Jour. Sci.*, XLVI (October, 1918), 551–57.

[2] G. K. Gilbert, *Report on the Geology of the Henry Mountains*, 1880.

[3] H. E. Gregory, "Geology of the Navajo Country," *U.S. Geol. Surv., Prof. Paper 93*, 1917.

[4] Whitman Cross, "Stratigraphic Results of a Reconnaissance in Western Colorado and Eastern Utah," *Jour. Geol.*, XV (1907), 634–79.

nature of these beds is best brought out by the illustrations. Figure 3 shows a sheer wall of the Vermilion Cliff; Figure 4 illustrates one of the characteristic arches developed by the curved lamination of the same formation, and, in addition, shows the overlying thin, shaly red sandstones of the supposed Todilto. In Figure 5 the same thin-bedded red sandstone is shown at the base, capped by a remarkable wall of the upper, or Gray Cliff, formation. In the foreground of Figure 6 is shown a low cliff of the Moenkopi capped with Shinarump conglomerate; above that, slopes exposing 500 to 600 feet of Dolores or Chinle shales (upper Shinarump shale); in the middle distance massive cliffs of the lower La Plata or Vermilion (Wingate?); next above are slightly thinner beds capping the cliff (probably Todilto); and finally in the background the amazing domes of the upper La Plata or Gray Cliff (Navajo?), which give the name of Capitol Wash to the canyon. Figure 7 also shows the three divisions of the La Plata here, the Vermilion Cliff below (the sheer wall), then the more shaly beds, and finally the Gray Cliff sandstone above with its characteristic domes.

FIG. 3.—Cliff of basal La Plata sandstone (Vermilion Cliff), in Mule Twist Canyon, Water Pocket Flexure, near Henry Mountains, Utah. (Vertical lines are not bedding, but probably water streaking.)

Near the base of the Flaming Gorge at this point are also massive tan sandstones identical with the La Plata (Figs. 8, 9, 10) and only distinguished from it by their position well above both divisions of the La Plata, as just described. In Water Pocket

Canyon the basal Flaming Gorge contains heavy gypsum beds occupying a position below this tan sandstone and above the twofold La Plata sandstones. In this locality the fossiliferous limestones were not noted by the writer, but they are reported by Gilbert[1] west of Masuk Plateau. The localities in Water Pocket Canyon are perhaps 30 or 40 miles southeast of where the Teasdale collection was made.

In the Water Pocket Canyon locality the Flaming Gorge beds supposed to be McElmo are directly overlain by sandstones that

FIG. 4.—Lower La Plata (Vermilion Cliff) sandstone, with characteristic arch, overlain by thin-bedded red sandy shale (Todilto?) in Mule Twist Canyon, Water Pocket Flexure, near Henry Mountains, Utah.

grade up into typical Mancos shale. From these sandstone beds the writer collected the following fossils along Bitter Creek Divide. Identifications were made by Dr. Stanton, who says:[2] "The collection from the sandstone near base of Mancos shale in Water Pocket Canyon yielded a number of species that are known to be characteristic of the sandstones in the lower part of the Mancos, as follows: *Ostrea prudentia* White; *Exogyra columbella* Meek; *Exogyra sp.*, related to *E. laeviuscula* Roemer;* *Exogyra sp.*, related to *E. ponderosa* Roemer;* *Gryphaea newberryi* Stanton;

[1] G. K. Gilbert, *op. cit.*, Fig. 2. [2] Personal communication.

*"White identified these two Texas species in collections from southeastern Utah and I repeated his descriptions and figures under the same names in *Bull. 106* but I now think them to be probably distinct."

Plicatula hydrotheca White; *Camptonectes platessa* White; *Astarte? sp.; Cardium trite* White; *Liopistha* (*Psilomya*) *elongata* Stanton."

This should serve to fix the Flaming Gorge, which is next below these sandstones, as at least in part McElmo, and the writer has shown, in the foregoing, that it lies above a sandstone with two definite divisions, believed to correspond to the La Plata.

FIG. 5.—Thin-bedded red sandy shale (Todilto?) capped with La Plata (Gray Cliff) sandstone, Mule Twist Canyon, Water Pocket Flexure, near Henry Mountains, Utah.

Unfortunately, at the point where the fossils were collected, the relations so plain in Water Pocket Canyon could not be seen, partly because of faulting and partly because of burial by lavas. However, there is but little doubt in the writer's mind that the Jurassic fossils were found in beds below typical McElmo and above the top of the La Plata. He believes that the McElmo formation is in its upper part equivalent to the Morrison, and that the lower beds, apparently equivalent to the Sundance of Wyoming, lie above the top of the true La Plata (Table I).

This is in marked contrast to the conclusions of Emery,[1] who considers that the Gray and Vermilion Cliff sandstones are both Wingate, that the fossiliferous gypsum-bearing beds of the writer's section are Todilto (middle La Plata), and that the sandstones placed in the McElmo by the writer are Navajo. As near as the writer can judge, Emery's chief reason for so believing is the lithologic similarity of the limestones of the type Todilto

[1] W. B. Emery, "The Green River Desert Section, Utah," *Amer. Jour. of Sci.*, XLVI (1918), 551–77.

Age	Gregory Navajo Country	Gilbert Henry Mountains†	Dake Present Paper	Emery Green River Desert	Gregory Interpretation of Powell	Emmons Green River Oil Field
						Dakota
					Dakota	
				Dakota		
			Dakota			

Age	Gregory Navajo Country	Gilbert Henry Mountains†	Dake Present Paper	Emery Green River Desert	Cross Intepretation of Powell	Lupton Green River Oil Field
Cretaceous	Dakota sandstone	Henry's Fork group (in part)	Dakota (locally absent)	Dakota	Dakota	Dakota
Lower Cretaceous or Jurassic	McElmo formation	Flaming Gorge group	McElmo Group: Upper McElmo; Salt Wash member; Lower McElmo (Sundance?)	Upper McElmo; Salt Wash member; La Plata Group: Navajo sandstone‡, Todilto formation	Flaming Gorge group	Upper McElmo; Salt Wash member; Lower McElmo
Jurassic	La Plata Group: Navajo sandstone; Toldito formation; Wingate sandstone	Gray Cliff sandstone; present, not differentiated; Vermilion Cliff sandstone	La Plata Group: Navajo sandstone; Todilto shaly sandstone; Wingate sandstone	La Plata Group: Wingate sandstone	White Cliff sandstone	La Plata sandstone
Triassic	Chinle formation; Shinarump conglomerate	Shinarump Group: Shinarump division "a"; Shinarump conglomerate	Dolores formation; Shinarump conglomerate	Chinle formation; Shinarump conglomerate	Vermilion Cliff; Shinarump Group: Upper Shinarump (Dolores)§; Shinarump conglomerate	
Permian (?)	DeChelly sandstone; Moenkopi	Shinarump Group: Shinarump division "c"	Moenkopi	Absent; Moenkopi	Shinarump Group: Lower Shinarump (Moenkopi)	
Pennsylvanian	Undifferentiated Pennsylvanian	Aubrey group	Kaibab limestone; Coconino sandstone	Pennsylvanian (?)	Aubrey group	

* Dotted lines indicate reported unconformities.
† Gilbert classes all formations between the Aubrey group and the Henry's Fork conglomerate as Jura-trias.
‡ Todilto and Navajo, as recognized by Emery, are considered by him to be Jurassic.
§ Powell classed the entire Shinarump group as Triassic.

with the fossiliferous horizons here described, and the fact that the Todilto seems to be thickening to the northwest from the type area.

FIG. 6—Looking into Capitol Wash, on road between Fruita and Notom, Utah. (M = Moenkopi, S = Shinarump, D = Dolores, W = La Plata [Wingate? or Vermilion Cliff], T = La Plata [Todilto?], N = La Plata [Navajo? or Gray Cliff]).

FIG. 7.—Dirty Devil Canyon, Fruita, Utah. Slope at base is Dolores, and the cliffs show three divisions of the La Plata.

Lee[1] comes to conclusions identical with those of Emery and cites many instances in southern Colorado and northern New

[1] W. T. Lee, "Early Mesozoic Physiography of the Southern Rocky Mountains," *Smithsonian Misc. Coll.*, LXIX, No. 4 (1918).

Mexico of the occurrence of limestones and gypsum above a sandstone which he calls repeatedly lower La Plata, or Wingate. The limestones and gypsum are correlated by him with the To "lto or

FIG 8.—Flaming Gorge (McElmo?) in Water Pocket Canyon, near Henry Mountains, Utah. The knobs of sandstone in the foreground overlie gypsum beds and are part of what Emery correlates as Navajo.

Photo by L. F. Zoller

FIG. 9.—Detail of sandstone beds of McElmo shown in Fig. 8 above

middle La Plata. In many of the sections referred to by Lee no sandstone at all is mentioned above the limestones and gypsum. In a few an overlying sandstone is described as probably upper La Plata or Navajo, but at no point does it seem, from his descriptions, to closely resemble typical Navajo.

The writer opposes the conclusions of Emery and Lee on the following grounds:

1. There are, at several other horizons in the La Plata, limestone lenses of character almost absolutely similar to the Todilto with which, on lithologic grounds alone, these fossiliferous beds might quite as well be correlated.

2. The limestones of the Todilto and all the other limestones of the La Plata are apparently absolutely non-fossiliferous, while these beds are packed with fossils.

3. As described by Gregory the Todilto is not a gypsum-bearing formation. On the other hand, the McElmo, where

Photo by L. F. Zoller

FIG. 10.—McElmo gypsiferous sandstone and shale, Water Pocket Canyon, Utah. These beds lie above the gypsum beds in dispute, and are considered Navajo by Emery.

definitely known to overlie true Navajo, though it does not carry gypsum beds, is repeatedly reported as highly gypsiferous. Gypsum is also an abundant constituent of the fossiliferous series in question. In a personal letter Dr. Stanton called the writer's attention to the fact that the section in question differed from typical McElmo in its numerous gypsum beds. The criticism applies even more positively in comparisons with the non-gypsiferous Todilto. If, as Lee suggests, the Todilto represents the fringe of the marine fossiliferous beds, along embayments where conditions were unfavorable to marine life, the gypsum-forming conditions should surely be presumed to persist into the Todilto area, a feature of the Todilto that Gregory does not mention.

4. That portion of the Flaming Gorge described by Emery as the Navajo is lithologically very unlike the type Navajo. Among these dissimilarities may be mentioned the presence of much shale and considerable gypsum in the Navajo as described by Emery, and their conspicuous absence in the Navajo of Gregory. Furthermore, Gregory describes much limestone as an almost universal characteristic near the top of the Navajo sandstone in its type region. The Navajo of Emery is apparently quite without such limestones.

5. According to Gregory, greenish tints prevail in the base of the McElmo. The basal part of the section measured by the writer also shows many greenish beds.

6. In the section measured by the writer, totaling 989 feet, in which only the lower 165 feet are clearly La Plata, there are 824 feet of beds, among which it is almost impossible to draw any boundary. They are certainly not all Todilto, or else the Todilto has thickened most enormously in this section. If they are in part Navajo, as must be the case, under Emery's conclusion, then the Navajo here grades inseparably into Todilto.

7. The McElmo, in Gregory's report, is described as extremely variable, but as prevailing sandy, with many intricately cross-bedded sandstone members, a description which fits well the characteristics of the supposed Navajo of Emery's paper.

8. If the basal part of the Flaming Gorge be considered as Todilto and Navajo, the total thickness of the La Plata group in the Water Pocket Canyon region will approximate 2,500 feet, which represents at least unusual thickening of the formation.

9. The old original classification by Gilbert represents a group of lithologic units with much more natural physical boundaries, at least in the area studied by the writer, than do those presented by Emery. In justice it must be said, however, that the writer has not seen the localities described in Emery's paper. His own section was measured about midway between the area studied by Emery and the Water Pocket Canyon, and he has studied the formations south but not north of that point.

10. The gypsiferous beds of northern New Mexico, so frequently mentioned by Lee, do not appear to be overlain by any beds that

can with confidence be referred to the Navajo. The sandy beds which he describes as occurring above the gypsum fit more closely Gregory's description of the sandstones above typical Navajo, being those considered by Gregory to constitute the McElmo. This discrepancy could be brought about either by a mistake in the identity of the sandstones called Wingate below the gypsum beds, or by the absence of any true Navajo, which condition would allow the gypsum beds at the base of the McElmo to rest directly on Wingate or Todilto.

From an extensive personal survey of these formations over a region that includes the Water Pocket Canyon, Dirty Devil Canyon, the Moab Valley, the Big Indian Uplift, the San Juan Uplift, the Fort Defiance Uplift, and the Zuni Uplift, the writer is reasonably familiar with the lithologic variations of these formations, and in view of the facts presented he is forced to the conclusion that these marine Jurassic beds are not the equivalent of the Todilto, but that they are above the Navajo sandstone.

Whether or not they are a part of the true McElmo is another matter. The writer is quite in accord with Emery in believing that a pronounced break occurs at the base of the Salt Wash conglomeratic sandstone. A similar break, with heavy conglomeratic beds, was noted by the writer at the Sundance-Morrison contact in the valley of the south fork of Shoshone River, Wyoming. The following is quoted from the unpublished manuscript of a bulletin on that region prepared by the writer for the Wyoming State Geological Survey: "At several points, particularly near the southeast corner of section 19, T. 51 N., R. 103 W., there lies between typical Sundance and typical Morrison from 5 to 20 feet of coarse pebbly sandstone. The pebbles are all small, mostly less than one-fourth inch in diameter, and consist of gray shale, gray sandstone, black chert, and quartz, mostly well worn and rounded." A break at this horizon, of great importance, is considered probable by Schuchert.[1]

This break, if sufficiently widespread, might well justify the separation of the beds below the Salt Wash member as a distinct formation, equivalent to the Sundance.

[1] Charles Schuchert, "Age of the American Morrison and East African Tendaguru Formations," *Bull Geol. Soc. America*, XXIX (1918), 245–80.

THE WEST POINT, TEXAS, SALT DOME
FREESTONE COUNTY

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INTRODUCTION

The West Point salt dome is a large, symmetrical structure of the salt-dome type occurring in the extreme southeastern corner of Freestone County, Texas. This dome structure is one of the most symmetrical and best defined, both geologically and topographically, of the North American salt domes, notwithstanding which it seems largely to have escaped the attention of geologists to the present time.

References to it in geologic literature are few and scant and no detailed description has yet been published. Deussen[1] referred to a dome in Freestone County as one of the inner belt of coastal domes, and Woodruff [2] first described the West Point dome generally, emphasizing particularly its fitness for study as a type example of salt-dome structure. Hopkins[3] included this dome, which he calls the Butler dome, on his index map showing the location of the Palestine dome, and Dumble[4] described it briefly under the same name.

The dome has been examined several times as a salt or petroleum prospect. Lee Hager reported upon it in 1908 and in his report mentions having examined it for private interests in 1907. Lewis C. Chapman reported on it in 1915 and various geologists of the

[1] Alexander Deussen, "The Humble, Texas, Oil Field," *Southwestern Assn. Pet. Geol., Bull. 1* (1917), pp. 60–79.

[2] In discussion of Deussen's paper. *Southwestern Assn. Pet. Geol., Bull. 1* (1917), pp. 79–84.

[3] Oliver B. Hopkins, "The Palestine Salt Dome, Anderson County, Texas," *U. S. Geol. Survey, Bull. 661g* (1917).

[4] E. T. Dumble, "Origin of the Texas Domes," *Amer. Inst. Min. Eng., Bull. 138* (June, 1918), pp. 1629–36.

Roxana Petroleum Company made a very careful and detailed geologic and topographic map of the dome about the same time.

The writer visited the West Point dome in 1916 with Lewis C. Chapman. He was so struck by the symmetry of the dome, the clear manner in which its structure is revealed, and its peculiar and characteristic topography that he resolved to study it more

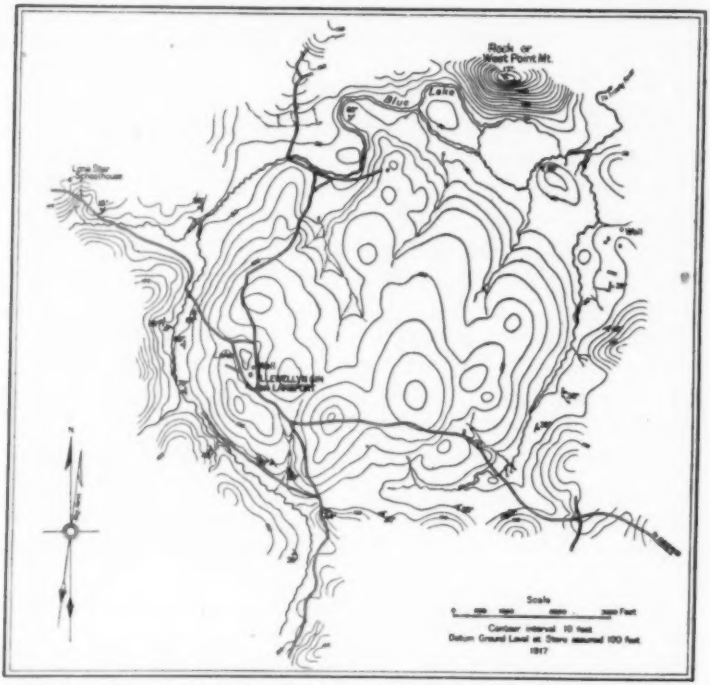

FIG. 1.—Topographic and geologic map of the West Point salt dome, Freestone County, Texas.

closely at the first opportunity as a type of salt-dome structure. This opportunity presented itself in November, 1917, and some five days were spent in making a rapid plane-table sketch of the dome.

The accompanying map (Fig. 1) is a result of this survey. Not enough time was available to make the detailed and extensive map which would better express fully the geology of the dome. Traverses

were run along the principal roads, around the circular drainage, and across the mound.

An attempt was made to express the drainage exactly, the essential topography, and sufficient dips and strikes to outline the dome structure. Many dip and strike observations could have been made in addition to those recorded. No attempt was made to map all of the springs and water seepages. A complete map of the dome should express in greater detail the topography outside of the circular strike drainage.

The writer has withheld this map in the hope of being able to make further field studies, but as the opportunity for such work seems remote, he offers the map in its present form as a contribution to the geology of salt domes. Acknowledgment is due and gratefully rendered to Earle S. Porter for his assistance in mapping the dome, to Lewis C. Chapman for much information regarding the dome, and to Sidney Powers, whose sketch and notes regarding a part of the dome the writer has seen.

LOCATION

The West Point salt dome lies some five to seven miles north of the town of Oakwood on the International and Great Northern Railroad, and extends from a mile or two east of Butler post-office to the western edge of the flood plain of the Trinity River (Fig. 2).

It is the southernmost known dome of the interior group of salt domes and forms a triangle with the nearby Palestine dome, the center of which lies some 9 miles N. 51° E., and with the Keechi dome, the center of which lies some 14.7 miles N. 34° E. from the center of the West Point dome. The remaining known domes of the interior group in Texas are the Brooks dome, some 39 miles N. 34° E.; the Steen dome, some 69 miles N. 27° E.; and Grand Saline, some 74 miles N. 9° E.

It will be noticed that West Point, Keechi, and the Brooks dome lie on a straight line striking N. 34° E. The Palestine and Steen domes lie near this line. This line of strike is roughly parallel to that of the Balcones fault, which strikes N. 25–30° E., and is some 70 miles distant, as well as roughly parallel to the belts formed by the outcrop of various Tertiary formations to the westward.

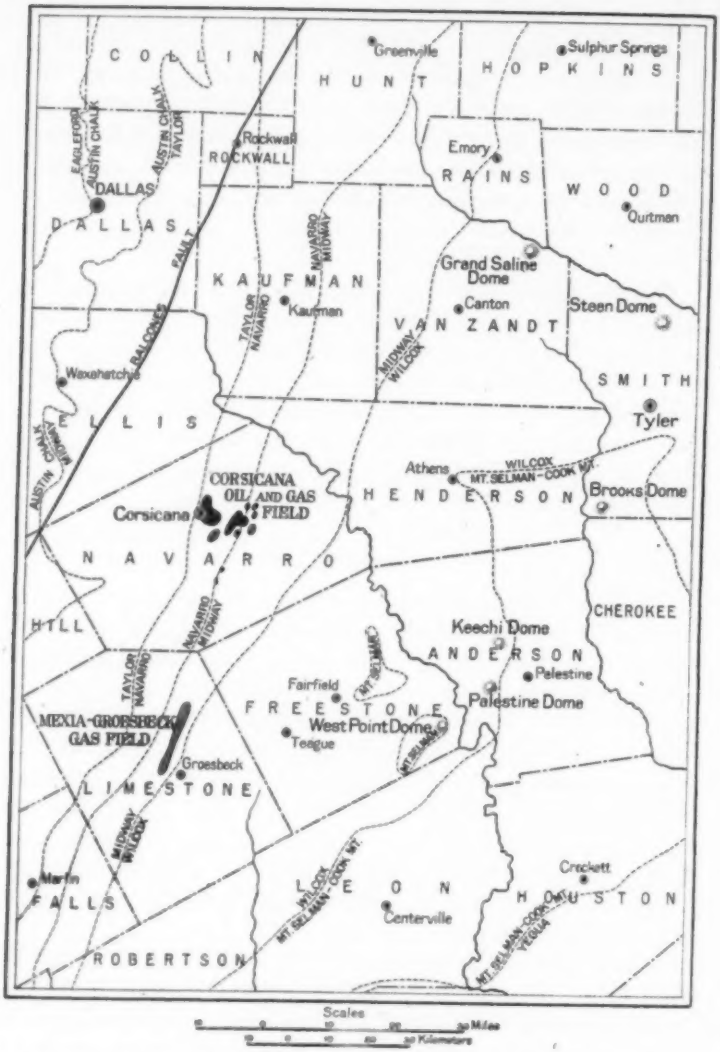

FIG. 2.—Index map showing location and relations of the West Point dome

This alignment and parallelism were recognized and mapped by Veatch[1] before he was aware of the existence of the Keechi and West Point domes.

Davis Hill, in Liberty County, some 110 miles S.SE., is the nearest of the known coastal salt domes, and the so-called Brenham dome is about the same distance S.SW.

The Batson and Saratoga fields, some 125 miles S.SE. from West Point, are the nearest proven oil fields with salt-dome structure. The nearest producing oil field of any type is the Powell pool of the Corsicana field, some 40 miles northwest, and the nearest producing gas field is the Mexia-Groesbeck field, some 37 miles due west of the West Point dome.

TOPOGRAPHY

Topographically, this dome consists essentially of an almost perfect circular mound surrounded by a ring-shaped valley, and this in turn is bounded on its outer margin by high hills having steep scarp faces toward the valley and long dip slopes away from it. This topography is so expressive that one would be justified in classifying this as a salt-dome structure on the basis of topographic evidence alone.

The mound forms in plane section an almost perfect circle 7,500 feet in diameter. The highest point is near its southern edge just opposite the divide between the two streams forming the ring-shaped encircling valley. The height of the mound here is sixty feet above that of the divide and one hundred feet above that of the junction of the two streams, the lowest point in the ring-shaped valley.

The mound is rather flat on top and dips steeply off to the valley on all sides, indicating that the erosion of the dome itself is not keeping pace with the cutting down of the valley. The erosion of this dome is developing regularly by means of channels and run-off normal to the major drainage, that of the ring-shaped valley. The longest draws or arroyos are those normal to the major drainage at its lowest point, and there seems to be no development

[1] A. C. Veatch, "The Salines of North Louisiana," *Geol. Survey Louisiana, Report of 1902*, pp. 41–100.

of laterals paralleling the ring-shaped drainage. This may be the result of the steep gradient of the draws and the softness of the Wilcox formation which covers the top of the mound, but it may also indicate that the beds on the top of the dome are not dipping so steeply as around its perimeter and consequently there is no tendency for strike drainage to develop.

The most striking feature of the topography is the comparatively broad ring-shaped valley which encircles the mound. This ring-shaped valley widens to a broad crescent-shaped area in its northeastern quadrant where the streams forming it come together and, passing through a gap just east of West Point Mountain, meander across the broad flood plain of the Trinity River to join it a short distance away.

The circular shape of this valley is due to the fact that streams forming have developed along the circular strike of the rocks around the salt dome or have been adjusted to it.

The principal stream is the one which comes into the dome at a point S.SE. of Llewellyn Gin, flows around its west and north sides through Blue Lake and, after being joined by the smaller eastern stream, flows off to Trinity River through the gap near West Point Mountain.

The fact that the direction of this stream where it comes into the dome is toward the West Point Mountain gap, by which it ultimately leaves it, suggests that it may previously have flowed directly across the dome and that it was adjusted to its present position by the formation of the dome.

The present drainage courses also suggest that this stream may have once flowed around the east side of the dome instead of the west side, as at present. The divide between the two streams is so low as to be almost imperceptible at the present time, and the direction of the draw just west of the road south from the Gin suggests that it was originally a tributary to the eastern drainage. If this suggested stream piracy actually occurred, it was probably effected by a tributary to the stream coming into the dome from south of the Lone Star schoolhouse and caused by more rapid erosion of the western channel resulting from the greater number of tributaries coming into it.

There is a gap, through which it is possible that the drainage once left this dome, about one-fourth of a mile south of the West Point Mountain gap.

The broadening of this valley into the crescent-shaped area already mentioned and the formation of Blue Lake and the imperfect drainage systems leading from it are evidently due to the drainage channels working down the dip toward the point of outlet and the fact that they have apparently reached the base-level of the Trinity River.

This ring-shaped valley, both in its narrow and broader courses, is a barren, open, prairie-like area covered with a sort of coarse marsh grass and is quite conspicuous because of its peculiar form and because of the vistas which it affords in this more or less wooded region.

Throughout the entire course of the valley, though occurring for the most part on its outer edge, are numerous springs and boggy places formed by the seeping of water. These springs are mostly of fresh water except for the salts leached from the formations from which they rise and which often forms incrustations of salt around the springs.

These springs are evidently formed by artesian water collected by the normally southeastward-dipping sands of the Wilcox formation over the large areas where it outcrops to the westward and coming to the surface here where the Wilcox is turned sharply upward around the edge of the salt core of the dome. The rarer brine and sulphurous water springs, some of which are found just south of West Point Mountain, doubtless rise from greater depths through faulting around the perimeter of the salt core.

Some of the brine springs near West Point have been worked intermittently for salt since before the Civil War.

These artesian springs bring up fine-grained sand and clay and thus form mounds, some examples of which are several feet across. Woodruff[1] cites the mounds formed along this ring-shaped valley, particularly on its north side, as excellent examples of the small mounds which are so typical of coastal-plain topography.

The outer circle of hills is generally higher than the inner mound and the hilly area extends off to the south and west in the dissected

[1] E. G. Woodruff, *op. cit.*

uplands formed by the rather extensive outlier of Mount Selman beds. To the northeast they extend but a short distance before the flood plain of the Trinity River is reached.

Though no investigation was made to determine whether or not there are more circular strike-drainage channels concentric to the valley mentioned in this hilly region, the writer strongly suspects that such drainge exists.

SURFACE GEOLOGY

The oldest rocks outcropping in the West Point dome are apparently the greenish-yellow clays and shales outcropping in the segment of the inner edge of the central mound lying between the road leading south from Llewellyn Gin and that leading from the Gin to the Lone Star schoolhouse. On a lithologic basis and guided by the apparent relation of these shales to the Wilcox formation, one would refer them to the Midway (Eocene) or Navarro-Taylor (Cretaceous) formations.

Sidney Powers has collected fossils from these shales or a horizon immediately above them at points respectively 1,000 feet NW.W. and 1,500 feet S.W. of Llewellyn Gin, and their age as published elsewhere[1] has been determined by Dr. C. Wythe Cook and Dr. L. W. Stephenson, of the United States Geological Survey, as Lower Eocene, either Midway or Wilcox and Upper Cretaceous.

On these bases the shales are assigned tentatively to the Midway Eocene and Navarro Upper Cretaceous. Dumble's[2] statement that this dome gives the same section as the Palestine salt dome, in which the outcrops of all of the formations of the Gulf series of the Cretaceous have been recognized, is clearly in error. The writer has seen no evidence of the outcrop, other than that just stated, of any Cretaceous rocks in this dome.

The center of the dome is covered with the very heavy sandy soil so characteristic of the Wilcox formation. Though not exhaustively searched, no outcrop of the country rock was seen

[1] The writer is very much indebted to the kindness of Dr. Powers for permission to use, in the present paper, these fossil determinations which he is discussing in greater detail elsewhere.

[2] E. T. Dumble, *op. cit.*

except an imperfect outcrop of a heavy yellow sandstone in the road some 1,500 feet due north of the Gin. This sandstone apparently pertains to the Wilcox, and it is believed that the central part of the dome is underlain by the Wilcox formation except in the area mentioned as probable Midway and Cretaceous outcrop. Chapman notes that an inlier of the Mount Selman beds is to be found in the central part of the dome, but this was not seen by the writer and, if present, is believed not to be in place.

All of the outcrops along the circular drainage valley which outlines the dome are of soft white, gray, and yellow sandstones and white, purple, and yellow shales of the Wilcox formation. Most of the dip and strike observations recorded were taken on bands of ironstone concretions in sandstones of this formation. The Wilcox formation also forms all of the lower hills and the base of the higher hills which form the outer edge of the circular drainage valley.

The upper part of the higher hills around the outer edge of the circular valley are composed of the characteristic ferruginous sandstones and conglomerates, in places iron ore, of the lower part of the Mount Selman beds, Claiborne, Eocene. The country rock for some miles to the west of this salt dome is of this same formation, though it apparently only caps the hills on the northeast. Hopkins[1] describes a section of the Wilcox in a bluff on the bank of the Trinity River at the mouth of Town Creek, some three miles northeast of the dome.

The dome lies at the easternmost point of a triangular-shaped outlier of Mount Selman beds. Another large irregular outlier of the same formation occurs in northeastern Freestone County. These outliers are cut off from the main body of Cook Mountain—Mount Selman formation, which lies to the eastward in Anderson County, by the broad valley of the Trinity River.

UNDERGROUND GEOLOGY

Some five wells, all comparatively shallow, have been drilled on or around the dome, but available information concerning them is scant and inexact; consequently we can do little but speculate

[1] Oliver B. Hopkins, *op. cit.*

regarding underground conditions. Lee Hager's report of July 7, 1908, on the Blue Lake oil field, states that some three wells had been drilled in the vicinity of Blue Lake up to that time.

The Oakwoods Oil Company is said to have drilled a well to a depth of 800 feet on the J. Strickland tract. A show of oil was reported. Two wells were drilled by the Gum Springs Oil Company, the first reaching a depth of some 1,220 feet and the second a depth of some 600 feet. All of these wells were drilled before 1908 and all of them were drilled in the vicinity of Blue Lake and West Point Mountain. None of them report salt.

At a later date at least two wells were drilled on the southwest side of the dome, one just north of Llewellyn Gin and the other just west of it. No detailed information regarding these wells was obtained. According to local report, the well north of the Gin, where casing still protrudes from the ground, was drilled to a depth of 700 feet and was drilling in rock salt when abandoned. The salt is said to have been struck at a depth of 300 feet.

The only log of any of these wells which is available to the writer is that of No. 1 well of the Gum Springs Oil Company, the deepest of the reported wells. According to Hager, this well was drilled on the east side of the "saline," a name which he gives to the wide valley just south of West Point Mountain. This well was evidently down on the flank of the dome. The log is quoted after Hager's report as follows:

Formation	Thickness in Feet	Depth in Feet
Soil	10	10
White running into dark sand	15	25
Soft slate and lignite	20	45
Alternating hard and soft shaly slate	46	91
Soft very black lignite	45	136
Brown sandy shale	27	163
Blue artesian water sand	71	234
Blue sandy rock	2	236
Brown shale	24	260
Alternating stratas soft coal, brown shale, and crystals of sulphur or paraffins	11	271
Black shale, blue sand with continuous particles of yellow honeycomb rock and strong gas and oil showings	39	310
Black shale	25	335
Black and brown shale, some sand, and pyrites	43	378

Formation	Thickness in Feet	Depth in Feet
Soft coal, brown shale, and pyrites	34	412
Brown shale and bowlders	29	441
Brown shale	25	466
Brown shale, gravel, and pyrites	18	484
Soft rock	2	486
Brown shale, considerable blue sand, and pyrites	31	517
(Missing)	...	....
Brown shale	3	555
Blue concreted sand bearing gas and strong sulphur water	5	560
Alternating dark brown shale, deep blue concreted sand, and considerable pyrites, here passed through 4 inches very hard pale rock, color of limestone, but upon test shows not to be limestone	16	576
Blue concreted sand	10	586
Dark brown gumbo with some black shale and pyrites	19	605
Dark blue gumbo	10	615
Blue sand, shale	2	617
Blue sand gumbo	13	630
Black, very hard shale	25	655
Very hard blue laminated rock	2½"	....
Blue sand and black shale	3	658
Very hard rock	3	661
Alternating stratas of black gumbo shale with concreted blue sand and numerous iron pyrite bowlders but no rock stratum	559	1,220

Artesian water flowing out of the well was encountered at 163 feet, and oil and gas were encountered from 271 to 319 feet. The gas is said to have had a sweet and pungent odor and to have burned with a blue flame.

Apparently at least the first 400 feet of this log represents the Wilcox formation. Below 400 feet the formations are possibly Wilcox and Midway for 200 to 250 feet, and the remainder of the log represents the Navarro formations.

Aside from the very scant information obtained from the wells, we can only argue by comparison and inference regarding underground conditions.

At the nearby Palestine dome the Midway is believed to be absent, but all of the various formations of the Gulf series of the Cretaceous outcrop in the center of the dome. No continuous section is exposed and consequently the thickness of the various formations cannot be determined.

At the Keechi dome the oldest outcropping formation is the Austin chalk, and the Midway is said to be absent by unconformity. The Texas Company has drilled five wells on the southeast flank of the dome to depths of 3,170, 2,297, 2,656, 2,454, and 3,048 feet respectively. These wells start in the Wilcox, some of them penetrate the Woodbine, and possibly the first well passed through the Woodbine. It is almost impossible to estimate the thickness of the varous formations from the log of these wells.

Near Freestone, about 22 miles S.SE. of the West Point dome, a well was drilled by the Freestone Syndicate, Inc., to a depth of 2,370 feet. This well started in the lower Wilcox or Midway and was evidently in the Eagle Ford when abandoned. The log of this well, according to Lewis C. Chapman, who had the drilling under observation and supervised the collection of samples, was as follows:

Well No. 1, R. A. Tacker

	Thickness	Depth
Wilcox formation	624	624
Midway formation	177	801
Navarro and Taylor formations	820	1,621
Austin chalk	529	2,150
Eagleford shales	220	2,370

This determination is based altogether on lithologic characteristics and is probably exact only for the Austin chalk. The Nacatoch sand member of the Navarro formation is believed to have been passed through from 1,196 to 1,215 feet.

The most exact information regarding the thickness of the various formations in this general region is the section given by Matson[1] and based chiefly on the log of a Magnolia Refining Company well at Corsicana, some 50 miles northwest of the West Point dome. The various formation thicknesses given by him are as follows:

Navarro formation	1,650 feet	2,135 feet
Navarro and Taylor formations	135 feet	
Taylor formation	350 feet	
Austin chalk	425 feet	
Eagleford clay	370 feet	
Woodbine sand	400 feet plus	

[1] G. C. Matson, "Gas Prospects South and Southeast of Dallas," *U.S. Geol. Survey, Bull. 629* (1916), pp. 77–119.

Below the Gulf series of the Upper Cretaceous come the Washita, Fredericksburg, and Trinity groups of the Comanchean, but it would probably require a well more than 3,500 feet deep to reach the uppermost of these formations on the West Point dome.

There is no information regarding the dome material, the salt, gypsums, or limestones of secondary origin, other than the report that rock salt was found at a depth of 300 feet and penetrated to a depth of some 700 feet in the well drilled at Llewellyn Gin. It is not known whether or not there is a cap rock present over the salt.

Structurally this dome is very symmetrical, as is indicated by the dip of the outcropping formations. From one's general knowledge of salt-dome structure he would suspect that the upper part of the salt mass, the intrusion of which gives rise to this structure, has the form of a very regular truncated cone. The very steep dips and outcrop of the older shale (Midway?) formation southwest of Llewellyn Gin indicate that the southwestern edge of the dome is the point of greatest upthrust and consequently the point where the salt lies at the shallowest depth from the surface. The upthrust in this dome has been 800 to 1,000 feet.

The rocks over the top of the salt mass are probably levellying or nearly so. Around the perimeter the dips are very high, 25°–80°, and away from the center of the dome. They decrease rapidly as one goes away from the dome.

Only the central part of the area affected by the uplift of this dome is shown on the attached map. The entire uplift doubtless has a diameter of 3 to 4 miles and an area of 7 to 12 square miles.

AGE OF DOME FORMATION

The Mount Selman beds of lowest Claiborne (Eocene) age, and the youngest rocks outcropping in this immediate region, dip away from the West Point dome in all directions. Since these beds were involved in the folding which resulted from the formation of this dome, it is evident that the intrusion of the salt mass was not completed before early Claiborne time and the entire process may have occurred at some period since then and down to quite recent time. In fact, the formation of this and similar domes may be a very slow and continuous process now going on.

The West Point dome is a geologic phenomenon so similar to the other interior domes, particularly the nearby Palestine and Keechi domes, that it is undoubtedly of similar origin and probably contemporaneous in formation with them. Deussen[1] argues that these domes "were clearly formed in late Cretaceous or early Tertiary time, as is evidenced very clearly in the case of the Keechi dome of Anderson County, where the Wilcox beds of the Eocene rest unconformably on the Navarro beds of upper Cretaceous, the Midway being absent." He further states that the high angle of dip of the Wilcox around these domes, in conjunction with the unconformity, is plain evidence that the growth of the salt core is the result of different movements at different times.

Hopkins[2] accepts, for the Palestine and Keechi domes, Deussen's theory of the initial uplift of the dome during pre-Midway time and the existence of the domes as islands in the Midway sea. This theory is of course proposed to explain the apparent absence of the Midway formations at both the Palestine and Keechi domes.

This theory is not tenable for the West Point dome, if, as has been suggested, part of the greenish-yellow shales which outcrop west of the Llewellyn Gin are of Midway age. Neither is the theory the only available one, nor, in the writer's opinion, the most satisfactory one, to account for the apparent absence of Midway outcrops at the other domes.

The country rock is very poorly exposed at the Keechi dome and not much better exposed in the Palestine dome. It is entirely possible that a formation composed chiefly of shale and only a few hundred feet thick, as is the Midway, and occurring in a structure where the rocks are dipping very steeply, may not be well exposed or may have been overlooked.

If the Midway is absent in the Keechi and Palestine domes, however, the writer would suggest that it may have been faulted out of the outcropping section by having an older formation, say the Navarro, punched through it from below, and into contact with a still younger formation, say the Wilcox, by the upthrust of the salt core.

[1] Alexander Deussen, *op. cit.*

[2] Oliver B. Hopkins, *op. cit.*

This very peculiar type of structure is common in the Roumanian salt domes, where it has been studied by Mrazec,[1] who has designated the salt-dome structure with intruded and faulted core—his *noyau de percement* or core piercement structure—as "diaper" structure. Deussen[2] describes this very type of "piercement" structure in the Humble field where he regards the "Black Shale" Yegua as having been punched upward through the overlying Catahoula-Fayette sandstone series.

It is the writer's opinion that these domes were formed during very late time. The youngest formations outcropping near the domes have been involved in the deformation resulting from the intrusion or formation of the salt plug in every instance. The extreme youth of most known salt domes is, to the writer, a most significant fact. Sediments of Quaternary, perhaps of recent age, have been involved in the formation of the salt domes of coastal Texas and Louisiana. Pleistocene sediments were markedly folded by the formation of the Mexican salt domes. The mother-formation from which the salt of the Roumanian and Transylvanian domes is supposed to have been derived is of Miocene age and many of the German salt domes pierce Tertiary strata.

All of this points to the extreme youth of salt domes. It is doubtful whether a salt dome whose formation can be established beyond doubt as having occurred in pre-Tertiary time can be cited. This suggests that salt domes are, as the geologic time-scale goes, only transient affairs, and consequently theories of origin implying long life or great age for a dome should be looked upon with suspicion.

OIL AND GAS POSSIBILITIES

The West Point salt dome is believed to be a structure of type suitable for the accumulation of oil and gas deposits in commercial quantities. The upthrust here is not so great as at the Palestine and Keechi domes and it seems probable that the sedimentary formations are less faulted and broken than at those domes. This condition favors the West Point dome.

[1] L. Mrazec, "Les Plis a noyaux de percement," *Bull. Soc. Sci. Bucarest*, 1906: *Monit. due Petrole Roumain*, X (1908), 915–16.

[2] Alexander Deussen, *op. cit.*

The series of rocks forming this structure include known petroliferous or gas-bearing formations as follows: the Navarro formation, Nacatoch sand, is gas-bearing in the Mexia-Groesbeck and Corsicana fields and oil-bearing in the northwestern Louisiana; the Taylor marl includes the oil-bearing formation at Corsicana; the Austin chalk is oil-bearing in the small fields near San Antonio; the Eagleford contains the gas-bearing Blossom sand member of northwestern Louisiana; and the Woodbine sands include oil-bearing formations in northwestern Louisiana.

A test well 3,500 feet deep on the upper part of the flank of the West Point dome should pass through this entire section of rocks.

The direct indications of the existence of oil or gas deposits in this dome consist of the gas and oil shows reported in various wells drilled around this dome, as already stated, and gas seeps and sulphurous water springs near West Point Mountain which have been reported by Chapman and Hager. No search for direct indications was made by the writer, and he is therefore unable to confirm their existence.

None of the salt domes of Texas or Louisiana have yielded gas deposits of marked commercial importance, though many of them have been the source of exceedingly rich oil deposits. None of the interior domes have yet yielded commercial oil production. Some heavy oil (8° Be.) was found in the Woodbine sands on the flank of the Keechi dome in the Texas Company's well No. 1 Barret and Greenwood.

Petroleum in commercial quantities in salt-dome structures of the Gulf coastal plain has as yet been found to occur only under one of the four following conditions: first, in the cavernous limestone and gypsum cap immediately overlying the top of the salt mass, the so-called "cap rock"; secondly, in sands pierced by the salt, abutting against and sealed by the salt, and dipping away from it, the so-called "lateral sands" or "deep sands"; thirdly, in sands or sandstones for the most part lenticular and occurring above the cap rock or the salt dome itself, the so-called "shallow sands" in the Humble, Batson, Spindletop, and other fields or the deep sands in the so-called "deeply buried domes" such as Goose Creek

and Edgerly; and fourthly, in sand lenses and shales on the sides of the dome.

By far the most important of these are the first and second types of occurrence. The fourth type of occurrence might well be included in the same class with the second type except at Humble, where they are quite distinct. The third type of occurrence is much more important than generally recognized and is generally confused with the "cap rock" or the first type of occurrence. Spindletop is a fair example of a field where all of the production, until quite recently, has been supposed to come from the cap rock but where, in fact, much of it has come from shallow sands above the cap rock.

In view of the results obtained in the well north of Llewellyn Gin, which was drilled to the salt without any oil or gas production, and particularly because of the shallow depth at which the salt was encountered, prospects for cap-rock or shallow-sand production on the West Point dome would seem to be very poor. This single well is not a sufficient test of these possibilities, but the shallow depth of the salt is an unfavorable condition.

The possibility of finding oil and gas in the Cretaceous rocks on the flank of the dome has hardly been touched and would seem to justify the drilling of several deep wells. The most attractive area is a circular strip extending around this dome and from the base of the central topographic mound to about a half mile from it.

In view of the failure of the wells of the Texas Company on the flank of the Keechi dome, oil prospectors do not regard the interior domes with much favor at the present time, but these Keechi tests prove nothing but the barrenness of the limited area on which they were drilled. Many salt domes of the coastal group had been prospected intermittently for years before production was found. This is true of West Columbia and Goose Creek, the two most important fields of the Gulf coastal plain today.

The West Point dome shows every surface evidence of being a possible container of oil and gas deposits and should be prospected.

EDITORIAL

JOSEPH BARRELL AND HIS WORK

Joseph Barrell, a younger contemporary of Dutton, Gilbert, Powell, and Van Hise, to name only the most eminent of those upon whose work he built and whom he survived, is outlived by a number of older geologists who recognized in him a rising leader in research, and who feel his loss deeply, as that of a strong, judicious, yet enthusiastic and sympathetic fellow-worker.

Born in 1869, Barrell entered upon his career at a time when the leading minds in geology were opening up bonanzas of fact and theory. Already notable progress had been made in development work. The early prospecting of the Great West which followed the Civil War had been succeeded by the organization of the United States Geological Survey and the consequent co-ordination of studies carried on by able men under the stimulus of companionship in a great opportunity. That companionship, previously divided among small and often antagonistic groups, became general and cordial in consequence of the founding of the Geological Society of America in 1889. Discussion, concession, and co-ordination replaced controversy and opened the way for permanent constructive effort. Barrell fitted pre-eminently into this environment, which emphasized truth and subordinated self.

His scientific life thus coincided with the golden era of geology in America. The brilliancy of its earlier years inspired his studies, and during the last two decades he himself has contributed notably to its advance. Estimating the relative contributions of enlightened nations to geology, he wrote as recently as March, 1919: "For the past generation America, under which name should be included both the United States and Canada, has held a position of world-leadership in that science." The place which he himself filled in that leadership his contemporaries cannot justly estimate. But there is unanimous recognition of the fact that he was one of the strongest of the younger leaders and a man of great promise.

Lehigh University trained Barrell. He received three degrees, Bachelor (1892), Engineer (1893), and Master (1897), from that institution, took the degree of Doctor of Philosophy at Yale in 1900, and was honored by that of Doctor of Science in 1916 by his Alma Mater. Prior to his studies at Yale he had both taught and practiced mining engineering, and he continued to be an engineer when he became a geologist. His reasoning is stamped with the precise habits of thought which distinguish the practical from the theoretical. It is told that he would often draw a diagram before he wrote a statement.

Barrell pursued geology with ardent scientific interest from 1898 on, and thus gave a score of years of the prime of his life to it. As assistant in field work of the United States Geological Survey (1899–1901) and as a teacher of the natural sciences, especially of zoölogy and geology at Lehigh (1900–1908), he prepared himself for advanced research in its greater problems, and while occupying the chair of structural geology at Yale (1908–19) he found the larger opportunity to develop his especial abilities as an Engineer of Science.

The phrase engineer of science is used with all regard and respect to distinguish Barrell's activities from those of his great associates, who are better known in the field of theoretical investigation. It is a prime function of the engineer to test assembled materials, in this case facts, before proceeding to build with them firm structures, in this case logical conclusions. His work is kept by professional standards within limits which are fixed by quantitative values. Excursions into the realm of theory beyond those limits Barrell allowed himself only in his latest thought. In so doing he gave evidence of a tendency to develop from the engineer into the natural philosopher, whose thought transcends analysis as imagination transcends mathematics. The great loss to science in Barrell's death is that this evolution of mind from so fertile a source was cut short when there was yet promise of a score of years of productive growth.

The engineer in geology is strikingly illustrated in Barrell's first important contribution to the science, an article on the relative importance of continental, littoral, and marine sediments. He set forth his method of studying sedimentary structures and their

origin as comprising, first, discussion of the conditions of formation of sediments; second, comparison of the areal and volumetric importance of the several kinds of deposits now forming; third, consideration of the probable changes in relative importance which may have occurred in the past; and fourth, presentation of detailed distinctions by which the several deposits may be recognized, with a view to separating and interpreting them in terms of geography and climate.

It may be said that this is the sound scientific method of proceeding from facts to interpretation. It is also sound engineering. It builds permanent structures. By means of it, in the paper referred to and by others in which he applied the distinguishing criteria of sedimentation to specific examples, Barrell made an important and essentially original contribution to geology in that he forced the recognition of continental, fluviatile, and eolian sediments among stratified rocks which had been previously regarded as of marine origin exclusively. He thus revolutionized the criteria of paleogeography and paleoclimatology.

Paleoclimatology is a field to which Barrell unlocked the gate, if indeed he may not be said to have discovered it. His article on relations between climate and terrestrial deposits traces the complex variations of temperature and rainfall and their effects upon sediments with such keen analytic power, such wealth of illustration, and such logic as to lay firmly the foundations of interpretation of terrestrial stratigraphy in terms of climate.

Among the great problems of the past thirty years in geology and geodesy there is none more congenial to a mind like Barrell's than that of the strength of the earth's crust. His investigation of the subject illustrates the conscientious thoroughness with which he did his work. He was so serious, so earnest in investigation, that he could not leave any aspect of a subject untouched. His presentation is therefore an exhaustive review, analysis, and critique of the contributions previously made, together with a statement of the deductions which he found reasonable. He attacked the complexities of the subject, not only as a geologist and engineer, but also as a mathematician. He did not hesitate to enter the lists against those who arm themselves with higher mathematics and who seem invulnerable to attack by geologists

unfamiliar with the weaknesses of their armor. In the *Strength of the Earth's Crust* Barrell demonstrated the character and quality of his mind. He was a great analyst.

It is of interest to contrast Barrell's method with Gilbert's in the discussion of the fundamental problems of isostasy. Gilbert was a co-worker with Dutton in the studies that gave birth to the concept. Dutton formulated the idea of isostasy in 1889, and Gilbert discussed the related problem of crustal strength in 1890 in *Lake Bonneville*, the manuscript of which, so far as it touched this subject, was under consideration in 1888 and earlier. Gilbert's last contribution to the subject was in 1913. It is a brief but comprehensive interpretation of anomalies of gravity. In the interval of twenty-five years he wrote but little on isostasy, although he was associated with Putnam in the initial studies of gravity intensities in the United States and followed Hayford's brilliant work with constant interest. He published far less in a quarter of a century of investigation than Barrell has given us in one group of articles. Barrell's analysis covers every part of the subject exhaustively, dissociates all its elements, weighs them, and recombines them. It is the product of extraordinary industry, activity, and thoroughness. Gilbert, a profound thinker, a philosopher, awaited patiently the unfolding of knowledge. He entered into no controversy. Nothing escaped him, but he was content to sketch the edifice of truth in terms of fundamental principles. He anticipated Barrell in conclusions as to the relative importance of rigidity and isostasy, which the latter's exhaustive analysis confirmed.

A work comparable in exhaustive treatment with Barrell's *Strength of the Earth's Crust* is his *Rhythms and Geologic Time*. Rhythms in denudation and rhythms in sedimentation are discussed through sixty pages, emphasis being laid upon the pulsatory character of uplifts and subsidences. In contrast to previous discussions the view is developed that "the deposition of nearly all sediments occurs just below the local base level, represented by wave-base or river-flood level, and is dependent on upward oscillations of base level or downward oscillations of the bottom." If this be so, it follows that there are numerous interruptions in the process of sedimentation, some of which are already known as

disconformities, while to others of lesser duration in general Barrell would apply the term "diastem." The recognition of diastems and disconformities greatly lengthens the estimates of geologic time based on sedimentation. This discussion is followed by a review of all previous estimates of geologic time, distinguishing those based on oceanic salts and on radioactivity. The latter is fully and favorably presented. The paper closes with a section on the convergence of evidence, in which the physical terrestrial phenomena are compared with those of biologic evolution and stellar evolution. The trend of the argument is toward the acceptance of a very great age for the earth, possibly fifteen hundred million years. But, on the other hand, the amount of solar energy due to gravitational infall is found to be but approximately 1 per cent of that which would have been radiated during that immense lapse of time, and Barrell is thus led to consider the probability that there are other sources of energy in the sun than gravitational condensation. He recognizes that the great concentrations of energy must have previously been stored, and concludes: "The scheme of the universe is more profound and the unknown is a little nearer than it was recently thought to be."

The planetesimal hypothesis of the genesis of the planets has taken a permanent place among the foundations of geologic theory in America. Reviewing Chamberlin's *Origin of the Earth* Barrell wrote:

> To gain a proper appreciation of the value of the investigations which are condensed in this volume we must compare the present state of thought upon the general subject with that of twenty years ago, before Chamberlin had begun to publish upon the hypotheses of earth-genesis. Measured by that perspective, this volume is seen to represent an advance in thought on this subject so great that the names of Chamberlin and Moulton must rank high among those scientists who have dealt constructively with that vast, vague, and remote problem, the origin of the earth. The subject of earth-genesis is now fairly on the road to scientific investigation in place of philosophic speculation.[1]

It was characteristic of Barrell that he should translate the thought of the last sentence into action and should proceed to investigate the subject of earth-genesis by applying tests to Chamberlin's hypothesis, or rather to the group of multiple hypotheses, some of which were adopted and some discarded by Chamberlin in

[1] *Science*, 1916.

reaching the final, most reasonable, conclusion, as he saw it. However, in judging alternatives, there are many opportunities for divergence of opinion, and among those which are offered in this particular case Barrell has seized upon the one which is most significant in separating two distinct lines of geologic inference: Did the earth grow up as a comparatively cold, solid globe, or did it become molten and cool down from that condition? The question turns upon the size of the planetesimals and their manner of infall. We may best let Barrell state the alternatives by quoting from a lecture delivered by him at Yale in November, 1916:

> Under the terms of either nebular or planetesimal hypothesis a scattered state of the planetary material is implied as a stage antecedent to the origin of the planets. Was this growth of the planets geologically slow or rapid? Did it take tens or hundreds of millions of years, or was it on the contrary largely accomplished in tens or hundreds of thousands of years? Was the material largely in dust-like or molecular form or was it to a large extent in nuclei of considerable size? From these different postulates very divergent consequences may be traced in the formative stages of the earth; and finally the present nature of the earth itself may speak in favor of one or the other of these views.
>
> Chamberlin adopts the hypothesis that the stages of earth-growth were very prolonged, even geologically speaking, and that the accretion was dominantly of dust-like or molecular particles. According to him the building up of the planets followed three stages: first, the direct condensation of the nuclear knots of the spirals into liquid or solid cores; second, the less direct collection of the outer or orbital and satellitesimal matter; third, the still slower gathering up of the planetesimal material scattered over the zone between adjacent planets. This third factor in Chamberlin's view is regarded as very important, and he believes this diffused matter contributed much of the earth's substance, very slowly and in dust-like form. This is one of the critical points in the details of the theory upon which turns much of the development of the following argument.
>
> Chamberlin conceives the earth to have been built up as a solid body, not to have been fluid or viscous at any time later than the early nuclear stage, and to have begun to hold an ocean by the time it contained thirty or forty per cent of the present mass. Such liquid rock as was generated by compression or radioactivity during earth-growth is regarded as having been kneaded and squeezed to the surface, where it solidified approximately as fast as it was formed. In earth-growth the denser planetesimal dust, he argues, tended to be somewhat segregated into the primitive ocean basins, and served to maintain in them, as the earth was built outward, a greater density than in the elevated zones between, establishing thus a relation between density and elevation.

It seems a debatable question if such a large proportion of the added material was necessarily dust-like and capable of being weathered, sorted, and distributed by the primitive atmosphere and ocean. . . . . In fact, from this beginning of earth-growth the preponderance of the evidence appears to the writer to be against those sub-hypotheses which Chamberlin has followed. This evidence, its bearings, and conclusions will form the following parts of this article. It will be of ultimate value to both lines of argument that each may be weighed against the other. . . . .

It appears to the writer that the chemical character of the igneous rocks, the limited depth of density variations in the crust, the limited amount of salt in the sea, the rotation period for the moon and planets, all point to a molten condition of the earth at the completion of its growth. . . . . The questions raised by this conclusion are: What mode of growth would have favored the molten state and how far did this precede the beginning of the geologic record as given by the oldest rocks exposed at the surface of the globe?[1]

Barrell then proceeds to discuss in terms appropriate to a lecture rather than to an analysis, as the occasion demanded, the significance of the planetoids, the indications of primordial tidal retardation, and the deductions which may be drawn from the limited amount of oceanic salt as to the age of the ocean. Condensed though it is, the argument is too long to be quoted here, but the description of the early stages of the earth, as Barrell conceived them, sheds light upon the tendency of his mental development:

The indications of primordial tidal retardation and the limited amount of salts in the sea both point to the conclusion that the earth was molten at the completion of its growth. The molten state suggests a rapid earth-growth due to an original clustering of the matter whose convergence built up the planet. Larger nuclei, hundreds of miles in diameter, and smaller ones comparable to the planetoids, moved in elliptic and nearly intercepting orbits. Mutual perturbations kept modifying these orbits and providing new chances for collisions, union, and growth. Such collisions led to a development of energy of impact sufficient to produce in the growing earth a molten state at least in the outer portions. The earth kept growing at the same time by sweeping up large quantities of finer material, but a molten state suggests that the greater growth was due to the infall of the larger nuclei. Finally but one outstanding nucleus, the moon, was left beside the earth, and the earth-moon system attained a condition of stability and completed growth.

After describing the state of the molten globe, which he conceives to have been surrounded "even in its molten stage by an

[1] The first of a group of lectures delivered before the Yale chapter of Sigma Xi during the academic year 1916–17, entitled "The Evolution of the Earth and Its Inhabitants. The Origin of the Earth," by Joseph Barrell.

envelope of water in the form of a deep and heavy atmosphere of water gas," forming an effective thermal blanket, Barrell continues:

> The effectiveness of the blanket depended upon the peculiarity of both water gas and carbon-dioxide in being opaque to the slow vibrations of dark heat, absorbing these near the bottom of the primitive atmosphere and re-radiating them from higher levels as long, slow heat waves. Strong convection currents carried up these heated gases from the superheated base to the higher levels of the atmosphere. There the chilling condensed the water vapor into a thick and universal canopy of cloud, boiling up like thunder heads from below, shedding continuously a downpour of acid rain, rain dissipated again into vapor as fast as the drops fell into the deeper and hotter strata of the atmosphere. The intensity of the vertical convection maintained a high electric tension. Incessant flashes of lightning linked as with living fiery tentacles the cloudy heavens to the lurid molten earth. Tremendous reverberations of thunder, unsensed by mortal ears, shook the atmosphere in the world-wide primeval storm. . . . .
>
> During the more rapid growth-stages the molecular and dust-like matter swept up by the earth settled like a never ceasing cloud of volcanic ash. The planetesimals of sand and gravel size were swept up by the earth many millions of times more abundantly than our meteors at the present time. Those meeting the earth with the higher velocities were consumed by impact. Over the hemisphere of night the otherwise invisible atmosphere above the cloud canopy scintillated with incessant flashes of light and trails of luminous dust. Bodies of larger size gave in their dissolution a still more brilliant display and penetrated to greater depths. At longer intervals, with Titanic rush and roar, a greater projectile, tens or even hundreds of miles in diameter, cleaved through the canopy of cloud, leaving a tumultuous maelstrom behind, drove almost unchecked through the dense atmosphere below, and, with world-wide commotion, was engulfed with development of fervid heat, within the molten sea.

Only he who has a sure grasp on the controls can safely essay a flight of the imagination where the conditions so surpass all experience. Barrell's earlier, intensely analytical work showed little evidence of the power of philosophic speculation, the scientific use of the imagination, which is nevertheless the parent of investigation, even as Chamberlin's thought is the father of Barrell's. Barrell would have fallen short of the full stature of the philosopher if he had not developed beyond the engineer. Such passages as those quoted above show that he had grown in imaginative power, and, being severely controlled by the logical habit of thought of his early engineering and scientific career, he would have used that power judiciously, greatly to the advantage and advancement of

science. His death has robbed us at the moment when his promise was greatest.

Barrell's work is not yet done; his service to science and to his fellow-men is still incomplete. He has left it in our hands and in those of the younger generations to come. His research, which he loved, is to be carried on. His example, which is inspiring, is to be followed. We may well ask, as suggested by Dr. Branner, How are young men to be trained up to become Barrells? His mental qualifications were not extraordinary. His schooling was not unusual. Yet he became a most unusual man.

The reason for Barrell's strength can be expressed in two words, thoroughness and breadth. Whatever Barrell did he did thoroughly. The articles cited in this memoir demonstrate that fact. But let it be borne in mind by any young man who would aspire to be like him that such thoroughness is a habit of slow growth. He who would possess it must begin soon and must determinedly will to be thorough. Barrell studied thoroughly, acquired knowledge thoroughly, so that he knew what he knew, not for today or tomorrow only, but for his lifetime. For that reason he was able also to be broad.

Breadth and thoroughness of knowledge are often considered incompatible, and it is true that thoroughness and specialization are commonly associated. But thoroughness in laying foundations is the basis of great breadth of superstructure. Barrell was thorough in acquiring the elements of mathematics, chemistry, physics, geology, meteorology, astronomy, and zoölogy. He knew well the general principles, the broad facts, the methods of each science. He was firmly founded in them. Thus, when he had occasion to study climates of the past he approached them with an understanding of climates of today. When he would discuss the strength of the earth he could command his mathematics and mechanics. When he undertook to explore the unknown realms of earth-genesis he was equipped with an understanding of astronomy and physics that supplied the seed from which to grow his tree of knowledge. When he gave his imagination flight it was on wings of strength that it soared, giving us confidence that it could soar safely and to great heights, whence the profound depths of the unknown might be searched.

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